Finite Resources and the World Economy

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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

History of energy consumption in the United States (1776-2012)

- Petroleum
- Natural gas
- Coal
- Nuclear
- Other renewables
- Hydroelectric
- Wood

Source: U.S. Energy Information Administration, AER Energy Perspectives and MER.
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
Lead prices

Inflation-adjusted lead prices

1650 1700 1750 1800 1850 1900 1950 2000
Zinc prices

Inflation-adjusted zinc prices
Copper prices

Inflation-adjusted copper prices
Price volatilities

Annual standard deviation of percentage change in price
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

\[
c_t + k_{t+1} = A k_t^\alpha e_t^\nu
\]

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

Hotelling (1931)'s general insights:

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

This implies

\[ \frac{p_{t+1}}{p_t} = 1 + r_t + \frac{1}{p_t} (mc_{t+1} - (1 + r_t)mc_t) \]

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:

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

A special case is Leontief \((\varepsilon = 0)\): \( y = \min \{ Ak^{\alpha l^{1-\alpha}}, A_e e \} \). 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

\[ y = F(x_1, x_2; A_1, A_2) = \left[ (1 - \gamma)(A_1x_1)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma (A_2x_2)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \]

and

\[ G(A_1, A_2) = A, \]

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 $g_{Ae}$ and allows estimation of frontier, as given by $G$. 
“Peak oil” around 1980.
Addressing increasing resource use

Idea: as a stylized example, consider the Leontief case

\[ y = \min \{ Ak^{\alpha} / (1 - \alpha), A_e e \}. \]

- Initially, \( e \) is “abundant”: \( A_e \), together with the available amount of the resource, \( R \), is high relative to \( Ak^{\alpha} / (1 - \alpha) \).
- 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 \( Ak^{\alpha} / (1 - \alpha) \).
- 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},

\[
\sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\sigma} - 1}{1 - \sigma}
\]

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

\[
A_{e,t+1}/A_{e,t} \equiv g_{A_{e,t}} = f_{e}(1 - n_t).
\]
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 $\rho$ higher than one (more than Cobb-Douglas).

\[ c_t + k_{t+1} = F \left( A_t k_t^{\alpha / (1-\alpha)}, A_{e,t} e_t \right) + (1 - \delta) k_t - B e_2^{\chi} \]

\[ e_t = \left[ (1 - \lambda) e_1^{\rho} + \lambda e_2^{\rho} \right]^\frac{\rho-1}{\rho-1} \]

\[ \sum_{t=0}^{\infty} e_{1,t} = R \]
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.