A Dynamic Model for Analysis of Fuel Cycle Economics

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Objectives

- Dynamics are central to the economic assessment of the fuel cycle.
  - One oft suggested reason for recycling spent fuel is a fear that a growing use of nuclear power will strain a limited supply of natural uranium, resulting in an increasing real price of uranium over time. What are the economics when the input price is increasing?
  - Advanced fuel cycles are a complex industrial chain stretching across a very long time frame. This demands some attention to alternative assumptions about the dynamics of input prices.
  - The complexity of the industrial chain that makes up any advanced fuel cycle also suggests that the economics may be sensitive to assumptions about the growth path of power production and the path of transition from one fuel cycle to another. Do the economics differ across these different assumptions?

Modeling Choices

- Construct a model that sacrifices granular detail and fidelity in exchange for (i) transparency, and (ii) flexibility with respect to the dynamics.
- Seeking insight, not hard numbers.
  - Calibration problem.

Results

- The levelized cost of electricity (LCOE) for a given fuel cycle is independent of the time profile of electricity produced.
  - There is no need to restrict our cost calculations to so-called ‘equilibrium’ conditions.
  - If we have the right definition of the LCOE, then the LCOE is accurate for all points along a growth path.
- The ‘equilibrium cost’ calculation that dominates the small literature on the economics of the fuel cycle is not a LCOE.
  - For examples, see EPRI (2007) and INL/Shropshire (2006).
  - Red flag: ‘equilibrium’.
  - Lacks any good reference.
- What’s missing?
  - A proper accounting for the timing of cash flow. The up-front expenditure required to accumulate the necessary capital stock and the necessary fuel stock. In finance parlance, it ignores working capital.
  - ‘Equilibrium’ rationale is logically flawed.
- What’s correct?
  - ‘Equilibrium cost’ does measure cash flow…
  - …except when they try to fix it.

Results (cont.)

- We derive the LCOE given an increasing price of uranium.
  - LCOE is a function of time.
  - LCOE function remains independent of the time profile of electricity production.
  - The LCOE for Fuel Cycle #1 is initially below the LCOE for Fuel Cycle #3 and climbs above it.
- Modeling the transition from one to the other… not yet completed.

Model

- Model reactor life and fuel use using exponential decay and non-atomic units.
  - FC#1
  - Thermal reactor capital stock, $K_{1H,t}$, with depreciation at a constant rate, δ_H, and investment in new/replacement capital at rate $k_{1H,t}$, so that $dK_{1H,t},/dt = k_{1H,t} - \delta_H K_{1H,t}$. A unit of new capital is purchased at cost p_{1HK}.
  - Stock of loaded fuel, $U_{1H,t}$, burned at a constant rate, b_H, and replaced with new fuel at rate $u_{1H,t}$, so that $dU_{1H,t},/dt = u_{1H,t} - b_H U_{1H,t}$. A unit of fresh fuel is purchased at cost p_{1HU}.
  - Spent fuel, denominated in units of initial fuel, is generated at a rate $w_{1H,t} = b_H U_{1H,t}$, and is disposed of as waste at cost p_{1HW}.
  - Time profile of electricity production is denoted $z_{1,t}$.
  - Fixed ratios for the production of electricity per unit of capital, ϕ_{HZK}, for the production of electricity per unit of loaded fuel, ϕ_{HZU}, and, by transitivity, the loading of fuel per unit of capital, ϕ_{HUK}. Cost of spent fuel disposal is denominated in terms of units of initial fuel

Illustrative Growth Paths for Power Production

- A constant rate of electricity output, $z_{1,t}$=1…
  - requires an initial stock of thermal reactors, $K_{1H,0} = \phi_{HKZ}$,
  - a constant rate of reinvestment, $k_{1H,t} = \delta_H K_{1H,0} = \delta_H \phi_{HKZ}$,
  - an initial stock of loaded fuel , $U_{1H,0} = \phi_{HUZ}$,
  - a constant rate of purchase of fresh fuel, $u_{1H,t} = b_H U_{1H,0} = b_H \phi_{HUZ}$, and
  - yields a constant stream of waste, $w_{1H,t} = b_H U_{1H,0} = b_H \phi_{HUZ}$.
- A constant rate of investment in reactors, $k_{1H,t}$ =1…
  - generates an increasing capital stock of thermal reactors, $K_{1H,t} = (1/\delta_H)(1 - e^{-\delta t})$, that gradually approaches a limiting level of $(1/\delta_H)$,
  - requires a rate of purchase of fresh fuel, $u_{1H,t} = \phi_{HUK} b_H (1/\delta_H)(1 - e^{-\delta t}) + \phi_{HUK} e^{-\delta t}$, which generates a stock of loaded fuel following a path like that of the capital stock, $U_{1H,t} = \phi_{HUK}(1/\delta_H)(1 - e^{-\delta t})$
  - generates a time profile of electricity production like the path of the thermal reactor capital stock, and
  - yields a similar time path of waste production.
- A constantly growing rate of electricity production, $z_{1,t} = e^{\gamma t}$.

LCOE for Fuel Cycle #1

- Definition of LCOE:

$$\int_0^{\infty} z_{1,t}\, p_{1Z}\, e^{-rt} dt = \int_0^{\infty} \left(u_{1H,t}\, p_{1HU} + k_{1H,t}\, p_{1HK} + w_{1H,t}\, p_{1HW} \right) e^{-rt} dt$$

the time profile of the total system's electricity production, $z_{1,t}$, appears to be central to the definition of LCOE

- Equation for LCOE:

$$p_{1Z} = p_{1HU}\, \phi_{HUZ} \left(r + b_H \right) + p_{1HK}\, \phi_{HKZ} \left(r + \delta_H \right) + p_{1HW}\, \phi_{HUZ}\, b_H$$

but in this model, the solution is independent of the time profile of the total system's electricity production, $z_{1,t}$

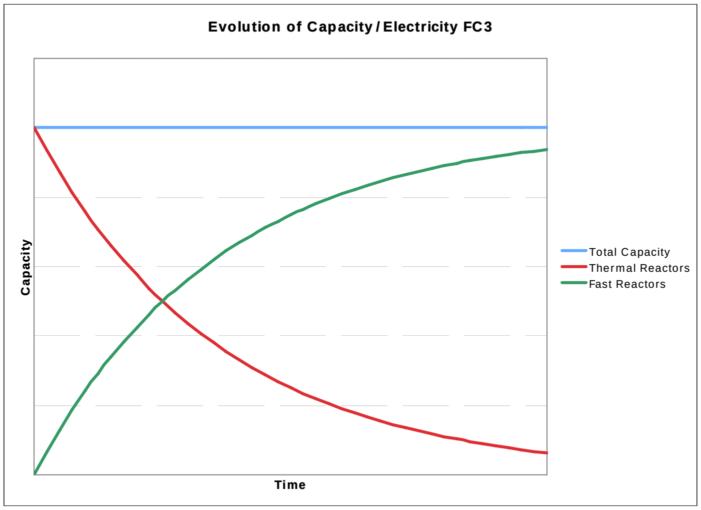
assuming a constant price level, constant technology structure

What actually matters, is the time profile of the electricity production from an individual unit–whether of capital or of fuel–does enter into the LCOE, yielding the expressions with the interest rate, depreciation rate, and burn rate.

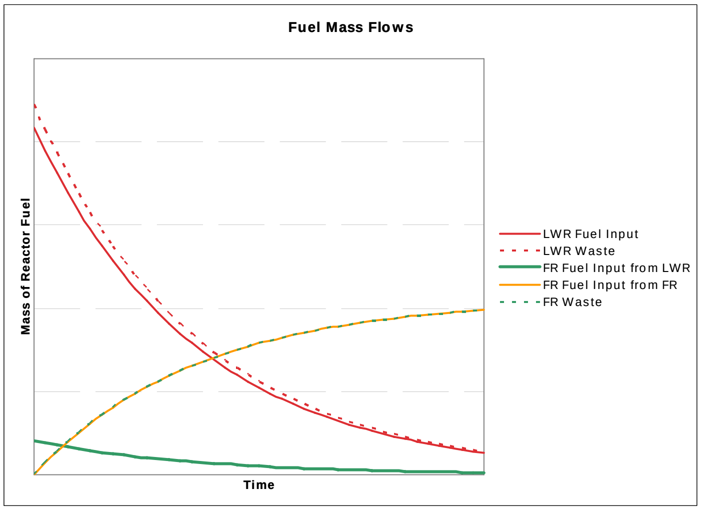
Model Continued

- FC#3
  - Thermal reactor module operates the same as before, except that the spent fuel is not disposed of in its entirety; spent fuel is reprocessed, separated into a stream of waste, $w_{3H,t} = b_H U_{3H,t}$, that is disposed of at a cost, p_{3HW}, and a stream of materials that are fabricated into fresh fuel for fast reactors, $u_{3HF,t} = \phi_{HFU} b_H U_{3H,t}$, at a cost of p_{3HFU}.
  - Fast reactor capital stock, $K_{3F,t}$, with depreciation at a constant rate, δ_F, and investment in new/replacement capital at rate $k_{3F,t}$, so that $dK_{3F,t}/dt = k_{3F,t} - \delta_F K_{3F,t}$. A unit of new capital is purchased at cost p_{3FK}.
  - Stock of loaded fast reactor fuel, $U_{3F,t}$, burned at a constant rate, b_F, and replaced with new fuel fabricated from spent thermal reactor fuel at rate $u_{3HF,t}$, and replaced with new fuel fabricated from spent fast reactor fuel at rate $u_{3FF,t}$, so that $dU_{3F,t}/dt = u_{3HF,t} + u_{3FF,t} - b_F U_{3F,t}$. A unit of fresh fuel fabricated from spent fast reactor fuel, $u_{3FF,t} = Cb_F U_{3F,t}$, where C is the conversion ratio, is purchased at cost p_{3FFU}.
  - A stream of waste from spent fast reactor fuel, denominated in units of initial fuel, is generated at a rate $w_{3F,t} = b_F U_{3F,t}$, and is disposed of at cost p_{3FW}.
  - Time profile of electricity production is denoted $z_{3,t}$.

Fast v. Thermal Reactors in Constant Production Path



Fast v. Thermal Fuel Mass Flows in Constant Production Path



‘Equilibrium Cost’ Concept

- Choose a time when the profile of costs is constant.
- Add up all costs realized at a point in time.

$$\pi_{1Z} = p_{1HU}\,\phi_{HUZ}\,b_H + p_{1HK}\,\phi_{HKZ}\,\delta_H + p_{1HW}\,\phi_{HUZ}\,b_H$$

- What is missing?

$$p_{1Z} = p_{1HU}\,\phi_{HUZ}\left(r + b_H\right) + p_{1HK}\,\phi_{HKZ}\left(r + \delta_H\right) + p_{1HW}\,\phi_{HUZ}\,b_H$$

$$p_{1Z} - \pi_{1Z} = p_{1HU}\,\phi_{HUZ}\,r + p_{1HK}\,\phi_{HKZ}\,r$$

LCOE for Fuel Cycle #3

- Definition of LCOE:

$$\int_0^\infty z_{3,t}\, p_{3Z}\, e^{-rt} dt = \int_0^\infty \Big(u_{3H,t}\, p_{1HU} + k_{3H,t}\, p_{1HK} + w_{3H,t}\, p_{3HW} + u_{3HF,t}\, p_{3HFU}$$

$$+ k_{3F,t}\, p_{3FK} + w_{3F,t}\, p_{3FW} + u_{3FF,t}\, p_{3FFU} \Big) e^{-rt}\, dt$$

- Equation for LCOE:

$$p_{3Z} = \beta \left[p_{1HU}\, \phi_{HUZ} \left(r + b_H \right) + p_{1HK}\, \phi_{HKZ} \left(r + \delta_H \right) + p_{3HW}\, \phi_{HUZ}\, b_H + p_{3HFU}\, \phi_{HUZ}\, b_H \right]$$

$$+ \left(1 - \beta \right) \left[p_{3FFU}\, \phi_{FUZ}\, Cb_F + p_{3FK}\, \phi_{FKZ} \left(r + \delta_F \right) + p_{3FW}\, \phi_{FUZ}\, b_F \right]$$

once again, the solution is independent of the time profile of the total system's electricity production, $z_{3,t}$

what it does reflect is the time profile of electricity production and associated costs from some standardized unit of initial investment—e.g., in a thermal reactor—and the consequent chain of investments in fast reactors and reprocessing

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Revising the Model for Changing Real Prices

- Illustrate using a growing price of uranium: $p_{1HU,t} = p_{1HU,0}\, e^{gt}$.
  - in this model the fuel price is an all inclusive number incorporating fabrication, etc., so this implies the full cost is increasing at the rate *g*.
- FC#1:

$$p_{1Z,t} = p_{1HU,t}\, \phi_{HUZ} \left(r + b_H - g \right) + p_{1HK}\, \phi_{HKZ} \left(r + \delta_H \right) + p_{1HW}\, \phi_{HUZ}\, b_H$$

Here, too, despite the growing price of uranium, the time profile of the total system's electricity production does not enter. The time profile of the electricity production from an individual unit is what enters, yielding the expressions with the interest rate, depreciation rate, price growth rate, and burn rate.

Modeling the Transition From One Cycle to Another

- Not completed.
- The key issue is the revaluation of the accumulated capital stock.
  - What is the time path for the economic value of a thermal reactor?
  - Does is grow at (r-δ_H)?
  - Does the rising price of uranium devalue the existing stock of thermal reactors?

The End

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