Economics of the Fuel Cycle

Guillaume De Roo & John E. Parsons

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Outline

- Part 1: The Fuel Cycle in Economic Perspective
  - 2 strategic issues
  - 3+ key alternative cycles
- Part 2: The Cost of the Fuel Cycle
  - Bottom line.
  - Key determinants and sources of uncertainty.

#1. Fuel Recycling to Maximize the Energy Extracted from Uranium Resources

- Advocates for recycling make much of the large share of uranium's potential energy unused by the traditional fuel cycle:

> *"What if the government allowed you to burn only 25 percent of every tank of gas? Or if Washington made you pour half of every gallon of milk down the drain? What if lawmakers forced us to bury 95 percent of our energy resources? That is exactly what Washington does when it comes to safe, affordable and CO_2-free nuclear energy. Indeed, 95 percent of the used fuel from America's 104 power reactors, which provide about 20 percent of the nation's electricity, could be recycled for future use. To create power, reactor fuel must contain 3-5 percent burnable uranium. Once the burnable uranium falls below that level, the fuel must be replaced. But this "spent" fuel generally retains about 95 percent of the uranium it started with, and that uranium can be recycled."*
>
> Heritage Foundation, 2007

- These "theoretical" measures of what could be may be a useful tool for guiding basic scientific research and exploring radically new technologies. But they are largely meaningless in guiding near term policy.
- Some "recycling" technologies only capture an additional few percentage points of the available potential energy, making the total potential energy a meaningless benchmark. The first question is, "What can we actually do?"
- Recycling is costly, not free. The second question is, "Is it worth it?" That's an economic tradeoff that needs to be explored based on the actual costs of competing technologies. Capturing all of the potential energy is certainly not going to be the optimal choice.

#2 Fuel Recycling to Minimize the Waste Produced

- Advocates also emphasize the reduction in waste that results from recycling:

> *"Recycling of nuclear fuel in other countries with proper safeguards and material controls under the auspices of the International Atomic Energy Agency (IAEA) has demonstrated the viability of high level waste volume reduction and energy resource conservation."*
>
> American Nuclear Society, 2007

- The volume or the mass of the waste is largely an irrelevant criterion.
- Recycling doesn't just "use up" the energy locked within the uranium. It changes the composition of the remaining matter.
- This may produce elements that are extremely dangerous to humankind. The key is not the total volume or mass of the leftover waste. The key is what it's made up of—the portfolio of waste products.
- There are many alternative recycling modes, and correspondingly many portfolios of potential waste products.
- Choosing among them is a complicated task that needs to be confronted deliberately. It cannot be reduced to a simple notion of more or less waste.

An Economist's Taxonomy of the Potential Cases for the Closed Fuel Cycle

- Case #1. The closed-cycle economizes on uranium consumption, thereby <u>lowering</u> the cost of electricity.
- Case #2. The closed-cycle produces a waste form that can be more economically disposed of, thereby <u>lowering</u> the cost of electricity.
- Case #3. The closed-cycle is chosen for non-economic reasons, despite the <u>higher</u> cost.
  - For example,
    - ✓ it has non-proliferation benefits, or,
    - ✓ it may produce a waste form that is more socially acceptable on risk or other grounds.
- …or a combination of the above…

3 Key Fuel Cycles per MIT *Future of Nuclear Power* (2003)

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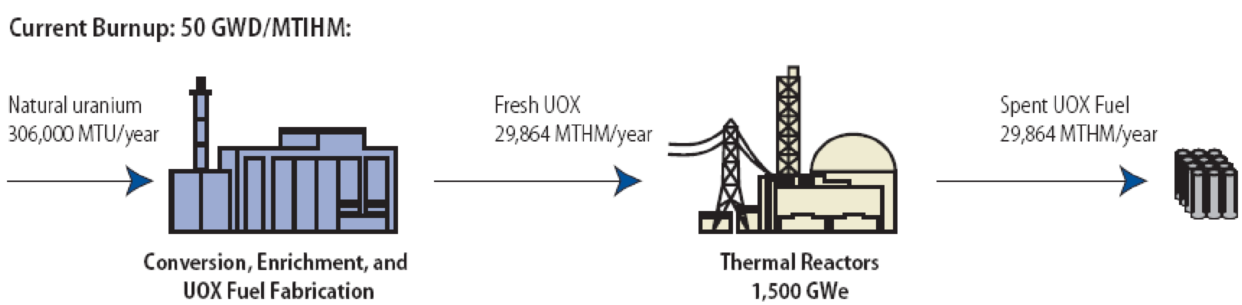
#1 Open Fuel Cycle: Once-Through Fuel

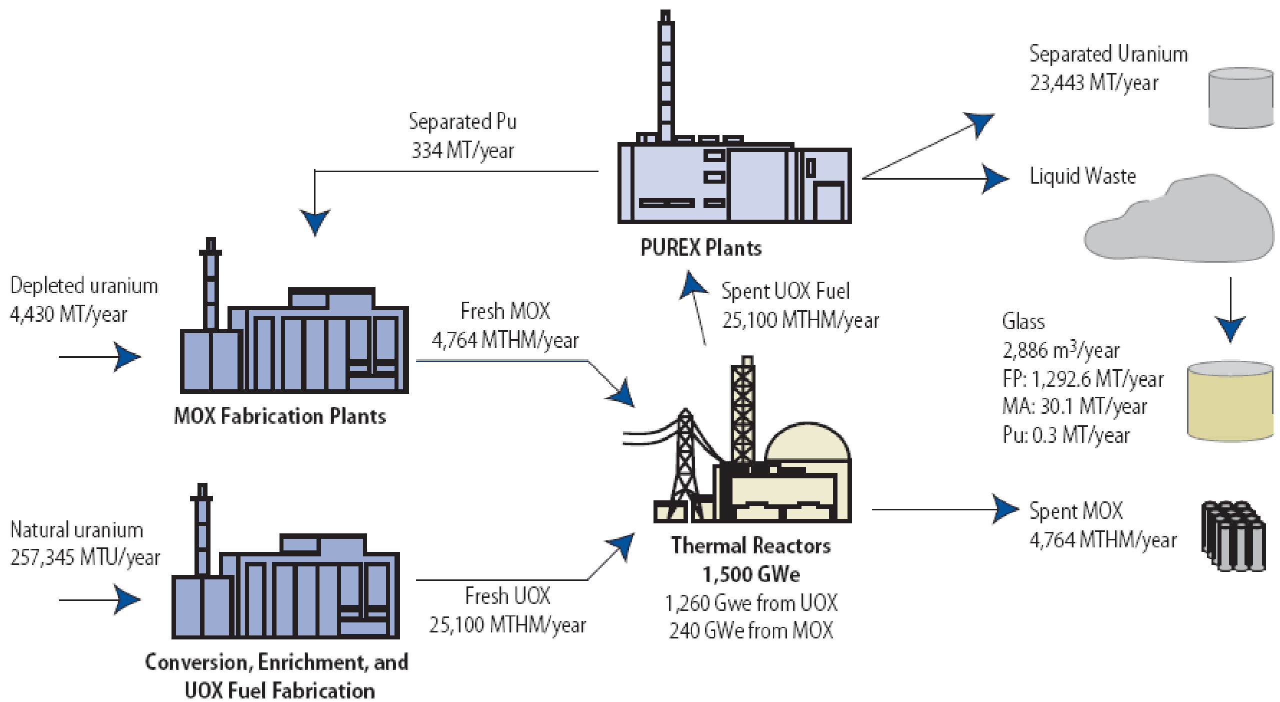
Figure 4.1 Open Fuel Cycle: Once-Through Fuel — Projected to 2050



- Current US system
- Light Water Reactors

#2 Closed Fuel Cycle: Plutonium Recycle (MOX option – one recycle)

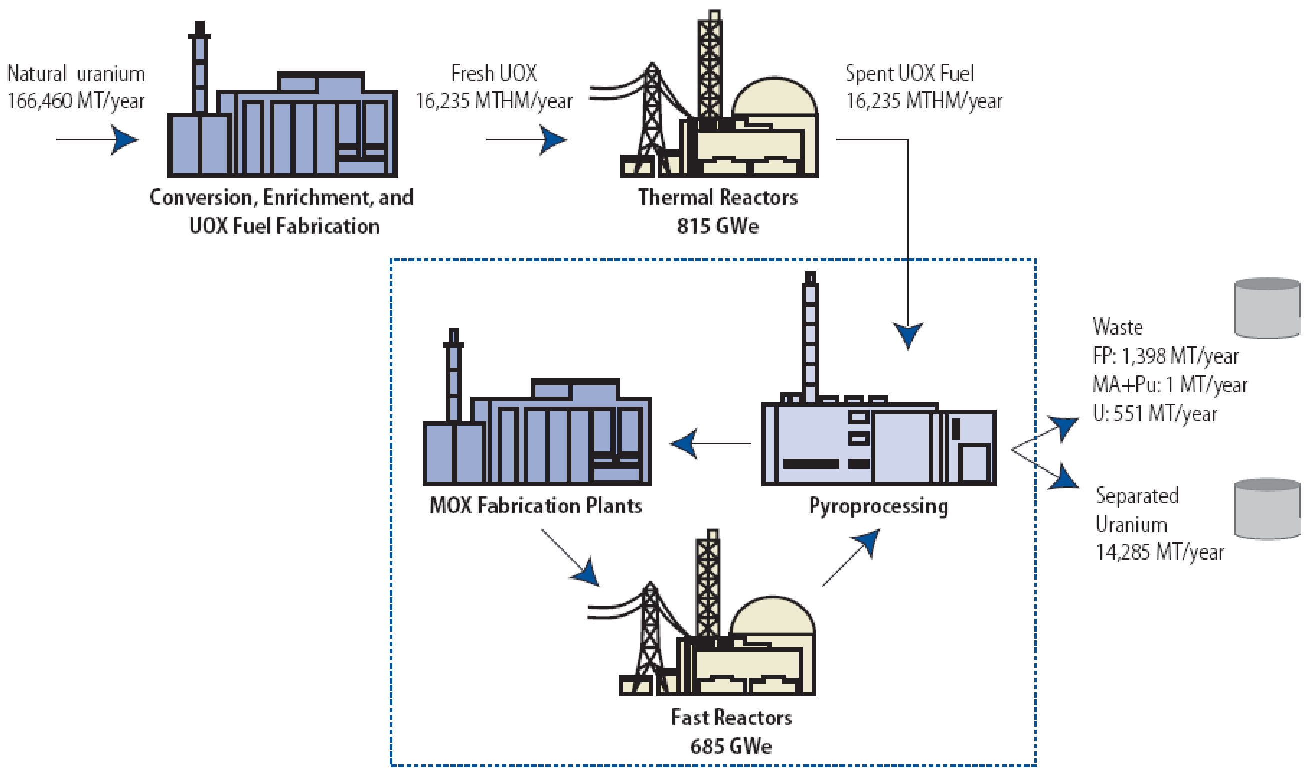
Figure 4.2 Closed Fuel Cycle: Plutonium Recycle (MOX option - one recycle) — Projected to 2050



- Current French system and the default system when people casually refer to recycling nuclear fuel
- Light Water Reactors

#3 Closed Fuel Cycle: Full Actinide Recycle

Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



- A mix of Light Water Reactors and Fast Reactors
- Not yet a functioning system anywhere. Many alternative versions.

Comments

- Much of the public policy discussion about recycling focuses on Cycle #2, the MOX option, because it is real.
  - John McCain in the 2nd Presidential debate with Obama.
  - The U.S. GNEP program has moved to near-term commercialization, implicitly adopting the PUREX process (leading to MOX fuel) which involves separated plutonium and light water reactors.
  - Academic studies of the costs & benefits of recycling focus
- But the MOX option…
  - Does not provide significant economy on uranium supplies, and
  - Does not provide economy or safety improvement w.r.t. disposal, and,
  - Produces separated plutonium.
- Cycle #3, the Fast Reactor actinide burning option includes many available variants…
  - Burner, breeder or balanced,
  - Many alternative reprocessing technologies yielding different portfolios of waste streams,
- Unfortunately, the freedom to choose may prove to be the enemy of designing a good choice.
  - The expert discussion about the closed fuel cycle is such a babel of alternative visions that it is difficult to pin down any single, comprehensive and coherent industrial structure from front end to back end that is sufficiently well defined that it can be costed. New concepts for advanced closed fuel cycles are advanced faster than old ones can be vetted.
  - While it is certainly unwise at such an early stage in the RD&D process to limit the focus to a single version of the closed fuel cycle, nevertheless, for certain purposes it is necessary to focus attention on a few key variants that are sufficiently well defined as to be meaningfully discussed and debated. The definition of these few key variants needs to be complete enough as to allow open expert understanding of the health and safety criteria and the costing. This has not yet been done.

The Cost of the Fuel Cycle

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Approach to Economic Valuation

- Metric: Levelized Cost of Electricity (LCOE) calculated from cost profiles of each cycle
- Preliminary Step: Use inputs from literature review
  - MIT Interdisciplinary Study (2003). The future of nuclear power
  - Bunn, M. et al (2003). The economics of reprocessing vs. direct disposal of spent nuclear fuel. Harvard Kennedy School
  - Shropshire, D. et al (2008). Advanced Fuel Cycle Cost Basis. Idaho National Laboratory
  - Boston Consulting Group (2006). Economic assessment of used nuclear fuel management in the United States
- Compare Cycles #1 and #3 in this presentation.
- Following Calculations:
  - All prices in 2007 dollars. Calculations are in real dollars. Assume zero real price escalation as a base case. Discount rate of 7%, real

LWR Once-Through Assumptions

- UOX
  - Burn-up of 50 MWd/kgHM (4.5% enrichment)
  - Natural uranium: $80/kgHM
  - Yellow cake conversion: $10/kgHM
  - $160/SWU, implying 6.37 SWUs
  - Fabrication: $250/kgHM

    …implying a front-end fuel cost of $6.9/MWh
  - Disposal Cost: $620/kgHM
  - Interim Storage: $200/kgHM

    …leading to a storage and disposal cost of $1.6/MWh
- Thermal Reactor Costs
  - Overnight capital cost $4,000/kW yielding a capital charge of $61.2/MWh
  - Non-fuel O&M costs inclusive of maintenance capital of $9.2/MW.
  - A 5-year pool storage period is embedded in these costs.

- Total LCOE $78.9/MWh

Key Additional Inputs for a Closed Cycle

- Costs for Reprocessing Spent Fuel
  - Capital costs for a reprocessing plant.
  - Operating costs for reprocessing.
  - Cost of producing fast reactor fuel
- Costs for Fast Reactors
  - Capital costs.
  - Operating costs.
- Disposal Costs for New Waste Streams

Closed-Cycle Additional Inputs

- Cost for reprocessing of spent UOX fuel
  - $1,600/kgHM
  - Yielding 93.6% mass in reprocessed uranium, 1.2% TRUs, and 5.1% HLW.
- Costs for producing UOX from reprocessed uranium
  - Conversion cost at 200% premium to conversion cost for natural uranium,
  - Enrichment cost at 10% premium to enrichment cost for natural uranium,
  - Fabrication cost at 7% premium to fabrication cost for natural uranium,
  - …implies a price for reprocessed uranium…$93.9/kgHM
- Cost for reprocessing of spent Fast Reactor fuel
  - $3,200/kgHM
  - Yielding 92.2% mass in U/TRU blend and 7.5% HLW
- Costs for producing Fast Reactor fuel
  - $2,400/kgHM (conservative, based on cost of producing MOX)

Closed-Cycle Additional Inputs (cont.)

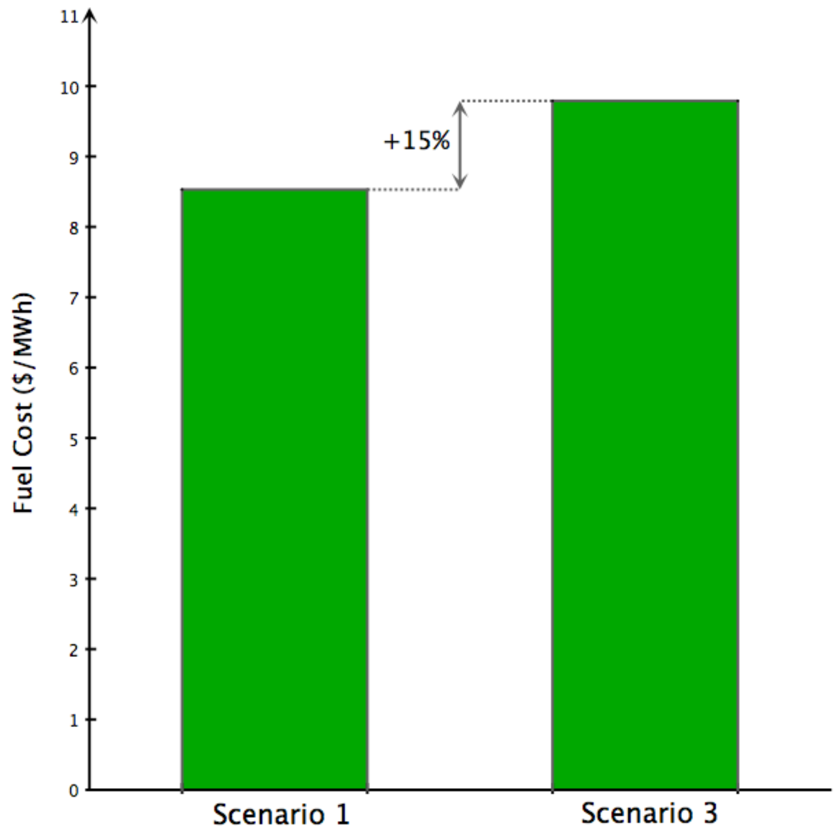
- Disposal costs for the closed fuel cycle waste products:
  - ✓ HLW from UOX: \$310/kgHM spent fuel … \$6,000/kgFP
  - ✓ HLW from FR: \$500/kgHM spent fuel … \$6,700/kgFP
- Fast reactor costs
  - Overnight capital cost 25% premium to a thermal reactor… yielding a capital charge of \$63.5/MWh
  - Non-fuel O&M costs of \$9.2/MWh

- Total LCOE \$82.5/MWh

A Cost Comparison Can Be Quoted 3 Different Ways: The Impression Varies Greatly

- #1 Fuel Costs Only
- Open Cycle / Once-Through
  - Uranium
  - Enrichment, conversion & fabrication
  - Storage & disposal
- Closed Cycle
  - Uranium
  - Enrichment, conversion & fabrication
  - Reprocessing & fast reactor fuel fabrication
  - Storage & disposal
- Result: closed cycle costs are higher by 15%

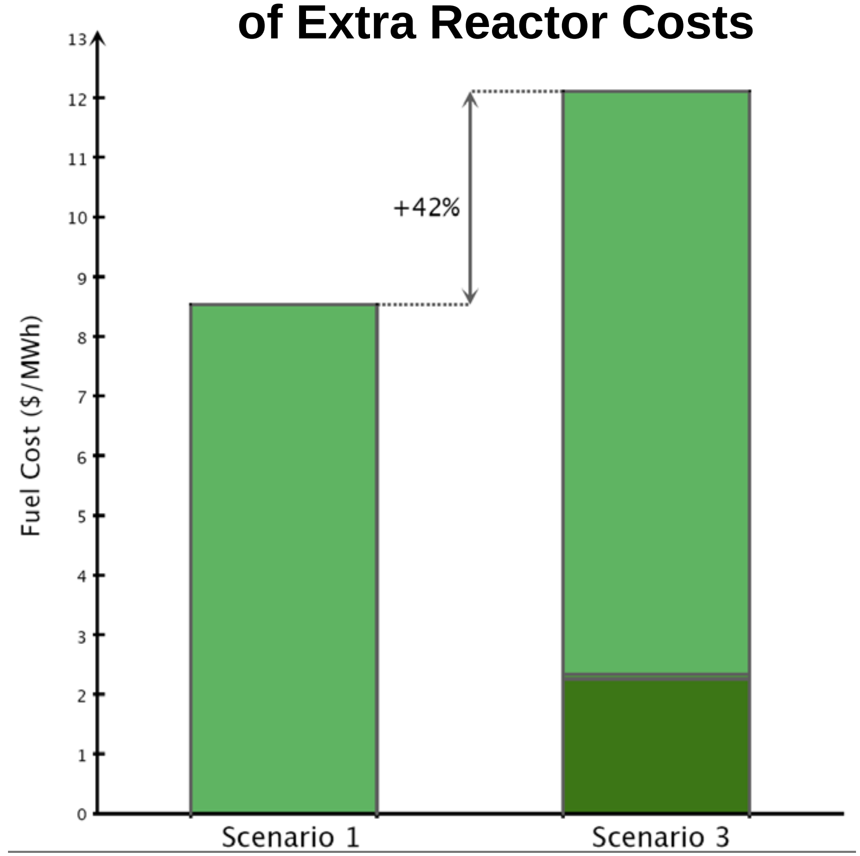
Comparing Fuel Costs Only



Where does one allocate the higher costs of the fast reactor system?

- #2 All additional costs required to move to a closed cycle
- Open Cycle / Once-Through
  - Uranium
  - Enrichment, conversion & fabrication
  - Storage & disposal
- Closed Cycle
  - Uranium
  - Enrichment, conversion & fabrication
  - Reprocessing & fast reactor fuel fabrication
  - Storage & disposal
  - **+ Extra Fast Reactor Costs**
- Result: closed cycle costs are higher by 42%

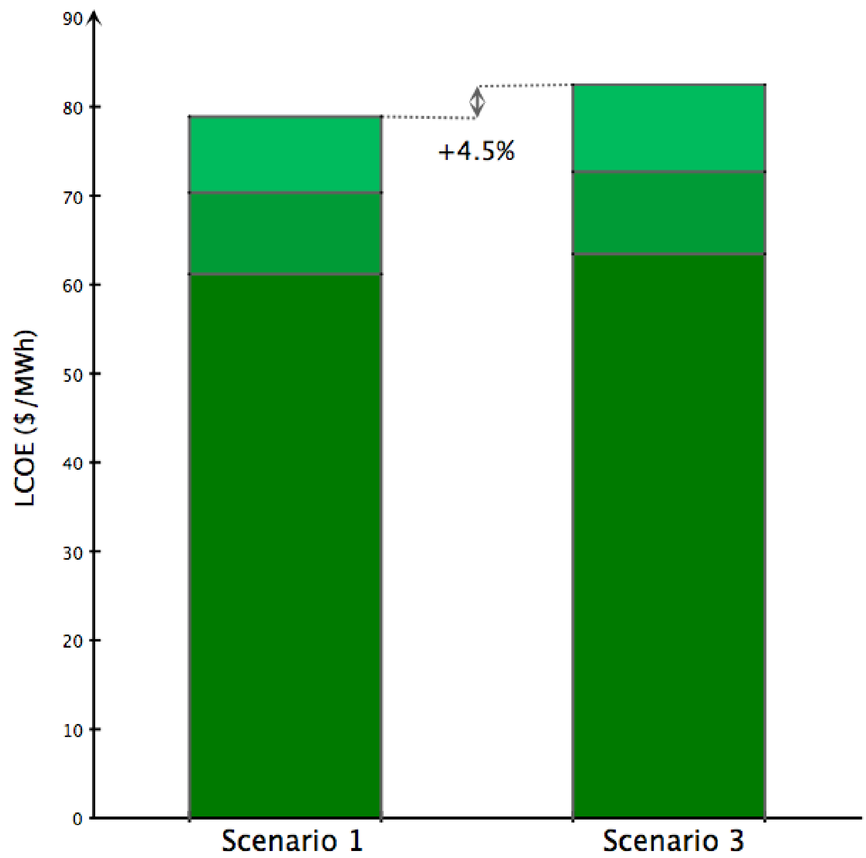
Comparing Fuel Costs Inclusive of Extra Reactor Costs



But Fuel Costs Are Only A Fraction Of LCOE

- #3 Compare total LCOE
- Extra fuel costs embedded in the overall total cost of producing electricity.
- Fuel costs in the Open, Once-Through cycle are only approximately 10% of the total LCOE.
- Therefore, the higher fuel costs of the closed-cycle only increase total LCOE by less than 5%.

Comparing Total LCOE



Results

- Calculated Increase: 4.5% of initial LCOE

- Fuel Cycle can increase by 15% with moderate impact on LCOE
  - High uncertainty in cost evaluation:
    - ✓ Use of reprocessing and fabrication processes not developed at full scale
    - ✓ Use of disposal costs for spent fuel and separated waste with no repository built (Yucca Mountain: 10% increase in 7 years, uncertain future)

- Main component of increase is the Fast Reactor Cost
  - Comparable uncertainty on the cost of commercial fast reactors from past prototypes

Takeaways

- Most studies clearly estimate a markedly higher cost for the closed fuel cycle.

- But… fuel cycle costs are a small fraction of the total LCOE.
  - Therefore the difference in total LCOE is not so large.
  - Closing the fuel cycle may make sense for non-economic reasons.
  - The higher LCOE purchases the non-economic benefits.

- Uncertainties in cost elements are large.
  - Fast reactor costs.
  - Disposal costs, whether for the once-through cycle or for the closed cycle.
  - Reprocessing costs.
  - The chosen version of cycle #3 hasn't been defined, let alone the cost of execution.

The End

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