Sample Cost Model (s) on BEFC

Guerman Kornilov, PhD

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Introduction

- Economics is a social science that deals with optimal distribution between the unlimited desires of people and limited natural resources.
- Economic analysis is a set of mathematical tools to find that optimal equilibrium. We all want the safe disposal, or re-use of the Spent Nuclear Fuel (SNF) and minimization if not elimination of all radioactive wastes. While we all want this, our resources are limited and thus the countries must make the optimal decisions how to achieve this.
- This presentation follows closely the economic model that was developed as part of the NEA study called "The Economics of the Back End of the Nuclear Fuel Cycle" © OECD 2013, Document No. 7061.
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Introduction of the Model (continued)

- The economic model is using the concept of Levelized Cost of Electricity. What this term means is a ratio of the two net present values (NPV): the numerator is the sum of discounted costs of construction, operation and decommissioning of the NPP and the denominator represents the discounted cash-flow associated with the revenues obtained from selling electricity at constant price.
- Furthermore, the fuel cycle component in the levelized cost of electricity is expressed in units of currency per unit of energy produced (e.g. USD per MWh). This is different from the more conventional use of the units of currency per unit of quantity of the fuel (e.g. USD/kgHM, USD per fuel assembly, etc.). However, in order to compare different fuel cycles with different fuel requirements, the concept of levelized costs is appropriate and it is applied.

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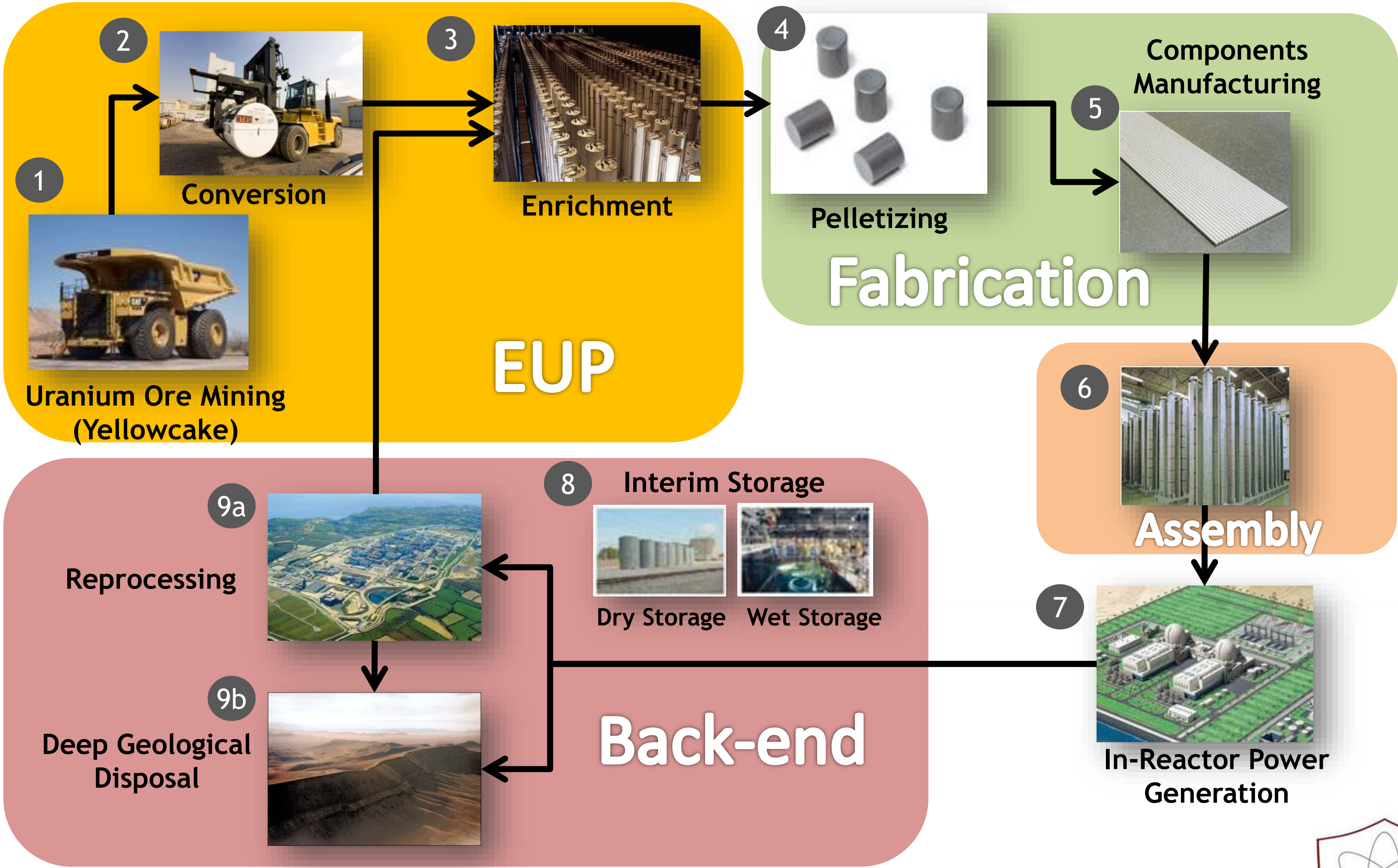
The Nuclear Fuel Cycle



Levelized Cost of Electricity

- Obviously, the Levelized Cost of Electricity (LCOE) consists of LCOE of the front end of the nuclear fuel cycle and LCOE of the back end. While the LCOE of the front end of the fuel cycle is straightforward to understand, the LCOE of the back end represents the Investment in the fuel storage, or reprocessing facility, the cost of Operating and Maintenance, the cost of Transportation and the Cost of Decommissioning of the back end facilities.
- Naturally, we need to consider here the costs of the spent nuclear fuel. For this, we need to apply a proper economic analysis. What are the key drivers?
- The total fuel cycle cost, which includes both procurement of the fresh nuclear fuel and the management of the SNF, represents a relatively small fraction (about 10-16%, depending on the discount rate) of the total LCOE for NPPs (see example below).

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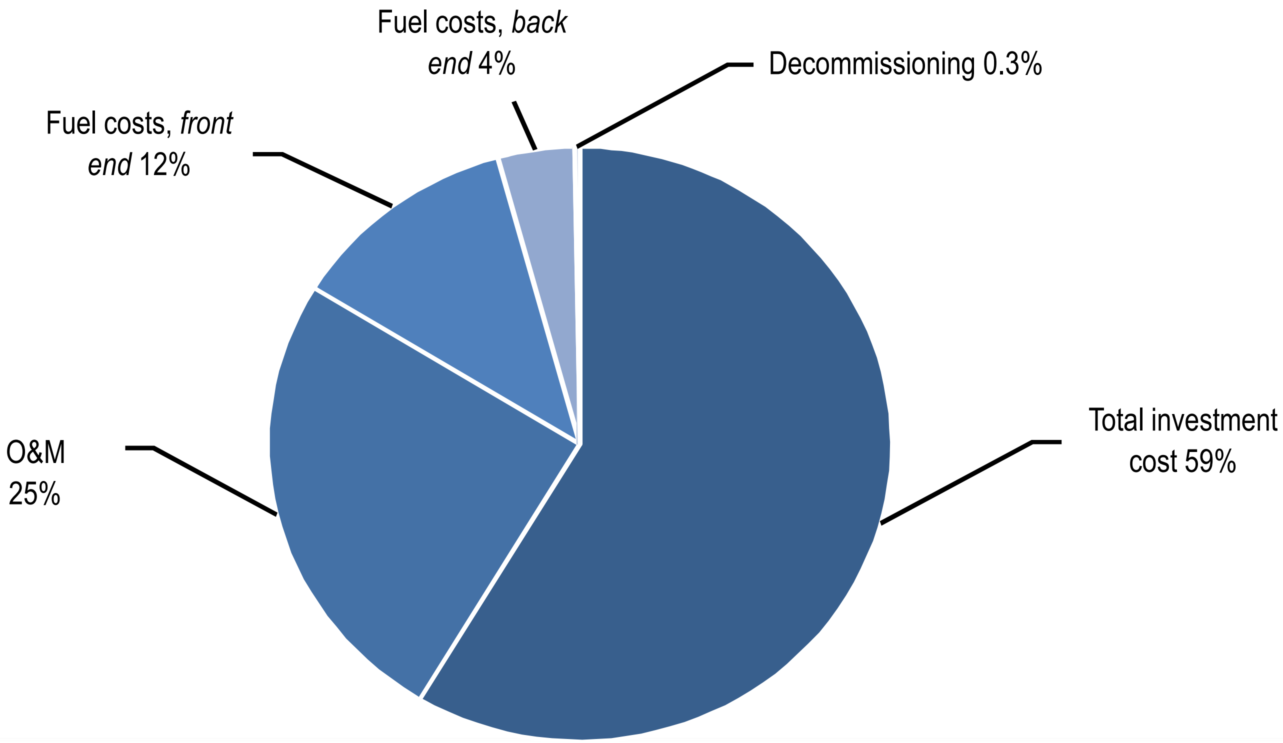
Structure of nuclear electricity generation cost



The pie chart above will look very different depending on the discount rate used (this one is for the discount rate of 5%)

Procurement of U3O8

- The number of the natural uranium producers is limited and it is not expanding. Hence, the risk is in availability of supply in the long run and in limited diversification of suppliers that leads to possible supply interruptions. Historically, natural uranium production has been below the demand level for the current global fleet of reactors. The balance was made through government inventories, especially of the US and Russia, and tails re-enrichment program.
- U3O8 is the easiest component of EUP to procure as it is practically a commodity (ASTM compliant).
- The utility must decide on the comfortable level of inventory. The level of inventory depends on several key factors, i.e. availability of the material in the market, the government policies towards uranium, etc. The utility shall design and implement its inventory policy based on the security of supply considerations.

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Procurement of Natural UF6 and/or Conversion Services

- Conversion from U3O8 is arguably the weakest link in the fuel supply chain and that represents the major risk. That is why some of the utilities hold inventories not in U3O8, but in natural hexafluoride (UF6) that results from the conversion process, or in both of these components. There are only three bona fade conversion suppliers in the world's free market: ConverDyn of the USA, Cameco of Canada and COMURHEX II facility in France.
- Transportation costs for UF6 is a major challenge as the product is not as expensive as EUP while transportation costs are similar.
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Procurement of Natural UF6 and/or Conversion Services (continued)

- Secondary supply from the US and Russian government inventories and tails re-enrichment to the natural UF6 level still suppress the market prices although they are gradually diminishing.
- Convertors themselves also buy UF6 from the market, thus creating an artificial shortage. Prices for conversion services are especially volatile and this represents a risk for the utilities.
- The near future of the conversion market should be closely monitored. ConverDyn actually increased capacity to 12 million kgU and could expand even further, to 15 million kgU.
- Westinghouse SFL facility in the UK is shut down.
- The new capacity requires significant CAPEX outflows that cannot be justified by the current level of prices.

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Procurement of the Enriched Uranium Product or Enrichment Services

- Enrichment represent a substantial part of the value of the final fuel assembly. For example, in the ready assembly natural uranium represents approximately 50% value, Conversion is about 5% value, Enrichment is 35% value and Fuel Fabrication is approximately 15% of the value (these ratios may change somewhat with the level of enrichment).
- Out of the Front-End Nuclear Fuel Cycle being valued at approximately $20 Billion a year, enrichment represents about 54 million SWU or $7 Billion, with the latter figure being highly dependent on prices that are now at the historic lows due to overcapacity.
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Procurement of the Fuel Fabrication

- Markets vary depending on region and fuel types. Current oversupply expected to continue. Vendors creating new alliances and partnerships.
- ORANO (~30% market share) -- PWR & BWR
- Westinghouse (~20% market share) -- PWR & BWR
- Global Nuclear Fuel (~10% market share) BWR only.
- TVEL and KEPCO Nuclear Fuel focus on domestic markets, but are aiming to be global PWR suppliers especially for the new build.
- Domestic plants are in Japan, Spain, China, and Brazil.
- Fuel fabrication is very specific to the type of the reactor, so the procurement options are very limited. Most of the utilities favor the performance and reliability/safety of the fuel assemblies of the price of fabrication.
- Totally unlike U3O8, fuel fab is not a commodity. Therefore, the market for Fuel Fabrication is also entirely different.

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Factors influencing the cost of the SNF management

- The factors that affect the back end fuel cycle depend largely on the strategy adopted for the SNF management.
- The direct disposal strategy would require the interim storage facility, the encapsulation facility, and a deep geological repository for the final disposal. For the fuel cycle strategies that involve reprocessing and recycling, the set of specific facilities are required: reprocessing plant, a MOX fuel fabrication plant, HLW vitrification plant, a waste conditioning plant, along with a final repository for the nuclear wastes.
- The economic model developed in the NEA 2013 study considers three major strategies:
  - Direct disposal of SNF;
  - Partial recycling in LWRs: Twice-through (REPUOX and MOX) and disposal of the spent MOX and spent REPUOX;
  - Multiple Pu recycling with LWRs and FRs: MOX and REPUOX recycling once in LWRs and multiple plutonium recycling in fast reactors.

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Structure of the model and input data

- The input data for the calculation of the total fuel cycle cost LCOE include:
- Size of the nuclear fleet of the particular operator: Total and constant NPP generation (in TWh/year). The economy of scale works.
- Discount rate: In most cases, the levelized costs were calculated for 0% and 3% real discount rates. Low discount rates are preferred for long-term public benefits projects.
- General fuel cycle characteristics: average enrichment, U-235 content in the enrichment tails, average fuel burn-up level for the fleet, average thermal efficiency of NPPs.
- Cost assumptions for the (uranium) front end.
- Overnight investment cost and O&M costs for facilities required for the implementation of the given SNF management strategy.
- Transport costs related to the back end and decommissioning costs of the back-end facilities.

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Model Results

- In all three major Strategies considered, i.e. direct disposal of SNF, the partial recycling in LWR and in multiple recycling, the fuel cycle cost component associated with the management of SNF is a relatively small fraction of the total levelized cost of electricity generation.
- The example of France is given to illustrate this. Historical cost of electricity generation in France is estimated to be at about USD 60/MWh. According to the results of this particular model, the total fuel cycle cost would represent less than 13% while the back-end cost would be about 6.5% of the historical cost. Note: the absolute numbers can still be big given the size of the fleet.
- The total fuel cycle costs calculated for the open fuel cycle option are the lowest. However, given the uncertainties related to cost estimates and their sensitivity to the discount rate, the difference between all three strategies are within the uncertainties.

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Model Results (continued)

- The additional costs associated with the reprocessing are being offset by the savings on the front end fuel costs.
- The specific costs obviously decrease with the size of the fleet and thus back end too. Thus, there may be economic benefits in sharing different fuel cycle facilities between countries/utilities:
- For small fleet of reactors, the fixed costs prevail, so costs rise as the size of the fleet decreases;
- For smaller fleets, uncertainties in the model also larger since smaller fleets produce less electricity.

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Other Models

Short title*	Description	Comparison of back-end processes for fuel cycle studies					Modelling environment
		Direct disposal	Reprocessing and recycling	Multiple recycling	Fast reactors	Partitioning and transmutation	
AFCI (2009)**	Advanced Fuel Cycle Initiative (Dixon, B., et al., 2008 and Shropshire D.E., et al., 2009)	√	√	√	√	√	**Static, dynamic**
MIT (2011)	MIT Nuclear Fuel Cycle Study (De Roo and Parsons, 2011)	√	√	√	√		**Pseudo-dynamic**
NEA (1994)	The Economics of the Nuclear Fuel Cycle (NEA, 1994)	√	√				**Static**
NEA (2006)	Advanced Nuclear Fuel Cycles and Radioactive Waste Management (NEA, 2006)	√	√	√	√	√	**Static**
Rothwell (2011)	The Value of Spent Nuclear Fuel Retrievability (Rothwell, G., et al., 2011)	√	√				**Static**
Harvard (2003)	The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel (Bunn, M., et al., 2003)	√	√	√	√		**Static**
BCG (2006)	Economic Assessment of Used Nuclear Fuel Management in the United States (BCG, 2006)	√	√				**Static**
Oxford (2011)	**Economic assessment of used and spent nuclear fuel management in the United Kingdom (Oxford, 2011)**	√	√				**Static**

Other Models

- The important point is that most of these models are relatively outdated just like the model in the NEA 2013 study that we discuss. Moreover, the assumptions used in the models are very specific to the objectives of the particular study and who ordered that study (the scientific institution, the government, etc.). Thus, the models are not strictly speaking directly comparable.
- One characteristic they have in common though. Most of these models are used to contrast and compare the one through (the open) cycle with various closed nuclear fuel cycles. Those closed cycles differ greatly in terms of technologies, specific requirements by the country, etc. Under these conditions, the models' produced outputs that were specific to the study are difficult to compare.
- Some models are concerned with non-economic analysis, but rather with non-proliferation, security of supply, transportation issues and legal aspects.

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- One characteristic they have in common though. Most of these models are used to contrast and compare the one through (the open) cycle with various closed nuclear fuel cycles. Those closed cycles differ greatly in terms of technologies, specific requirements by the country, etc. Under these conditions, the models' produced outputs that were specific to the study are difficult to compare.
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Conclusions

- The results of modelling by NEA 2013 are generally comparable to the results of other studies/models. However, the results are highly sensitive to the size of the reactor fleet, discount rate and the input data used.
- One of the major back-end fuel cycle cost factors in the open fuel cycle is deep geological disposal.
- The cost of interim storage becomes significant at larger discount rates.
- All figures in all the models, including the input data in NEA 2013 study need to be updated to the current prices (from 2010).

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Questions?

- This concludes the presentation. Questions are welcome!

The template of this presentation was kindly provided by Ms. Maja Verfondern