Front-end uranium mining market evaluation using a uranium market clearing model with a rules-based challenge approach

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Overview

- Uranium (U) mining and enrichment are steps in the **front end** of the nuclear fuel cycle (NFC)

- Competitive markets exist for these services

- They provide enriched U fuel to **nuclear reactors**, whose demand for fuel is **nearly inelastic** in the short run
Overview

• We are using a market-clearing model that evaluates the evolution of these markets through 2030:
  • primary uranium from mines,
  • secondary uranium from e.g. depleted uranium (DU) upgrading or highly enriched uranium (HEU) down blending
  • conversion to uranium hexafluoride (UF$_6$),
  • enrichment to 4-5% $^{235}$U, as required by most reactors.

• The model is not used to predict prices, but rather to evaluate policy measures affecting the front end markets, while taking a stochastic approach to account for uncertainties
Supply databases

• Primary uranium (CSM):
  - contains more than 350 uranium properties at various stages of development, representing reserves and resources of over 7 million tonnes U (tU).

• Secondary uranium (UT-Austin):
  - includes inventories of excess HEU, DU, other government- and utility-held U stocks, and excess weapons grade plutonium (WGPu)

• Enrichment (UT-Austin)
  - Existing capacity as well as announced and planned expansions through 2018; growth assumed thereafter

*CSM - Colorado School of Mines
** UT - Austin - University of Texas at Austin
Supply curve construction

Table 1. Reference data for costs calculation from the WISE Uranium Project Calculators

<table>
<thead>
<tr>
<th>Type</th>
<th>UG</th>
<th>OP</th>
<th>ISL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from Ref. (3):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC, $</td>
<td>2.81e8</td>
<td>3.47e8</td>
<td>1.11e8</td>
</tr>
<tr>
<td>OM, $/yr</td>
<td>1.04e8</td>
<td>1.62e8</td>
<td>1.73e7</td>
</tr>
<tr>
<td>DD, $</td>
<td>3.39e7</td>
<td>5.92e7</td>
<td>2.86e7</td>
</tr>
<tr>
<td>M, kg/yr</td>
<td>7.72e5</td>
<td>3.16e6</td>
<td>4.12e5</td>
</tr>
<tr>
<td>Calculated from data following procedure in text:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACC, $/yr</td>
<td>4.25e7</td>
<td>7.93e7</td>
<td>2.67e7</td>
</tr>
<tr>
<td>ADD, $/yr</td>
<td>1.07e6</td>
<td>5.78e6</td>
<td>3.07e6</td>
</tr>
<tr>
<td>IDC, $</td>
<td>4.36e7</td>
<td>5.37e7</td>
<td>1.72e7</td>
</tr>
<tr>
<td>UC, $/kg U</td>
<td>192</td>
<td>77.9</td>
<td>114</td>
</tr>
</tbody>
</table>

\[
ACC = \frac{UC}{UC_r} \cdot \frac{ACC_r}{M_r},
\]

\[
OM = OM_r \cdot \frac{UC}{UC_r} \cdot \frac{M}{M_r},
\]

\[
DD = ADD_r \cdot \frac{UC}{UC_r} \cdot \frac{M}{M_r},
\]

\[
IDC = IDC_r \cdot \frac{UC}{UC_r} \cdot \frac{M}{M_r},
\]

\[
\begin{align*}
P_1 &= axQ_1^2 + bQ_1 + c \\
P_2 &= aQ_2^2 + bQ_2 + c \quad ,
\end{align*}
\]

\[
0 = 2aQ_2 + b
\]

Total supply curve
Demand curve construction

- **Demand curves** are calculated as the **locus of points** that minimise cost, $C \left[ \right]$, to the consumer:

\[
C = (P_U + P_C) \cdot U_d + P_{SWU} \cdot SWU_d
\]

$P_U, P_C, P_{SWU} =$ market prices of U, conversion, enrichment [$/kg or $/SWU]

$U_d, SWU_d, NU_d =$ amount [kg or SWU] of U or SWU

**Each term is a function of the DU ‘tails’ U-235 enrichment, $x_w$**

(and the reactor fuel and natural uranium enrichments $x_p$ and $x_f$).

- **Constraints:**
  - Demand for reactor fuel (fixed in the short run) must be satisfied
  - $P_U$ treated as free, $P_{SWU} = f(SWU_d)$ obtained from clearing enrichment market at each trial $x_w$
Market price calculation

• All uranium mines can potentially produce in a given time period if the price is high enough

Supply and demand curve example
Outline

• Importance
  • Measure policy effect on a U market price
  • Assure policy sustainability
  • Introduce rule engine concept

• Methodology
  • Profit accumulation model
  • Time delay module
  • Uranium bank module
  • Global uranium bank
  • Rules engine

• Test case
  • Tests with rules challenge approach
Methodology

• Profit accumulation model
  • Distribute earning back to investors
  • Cover future losses
  • Protection against U market price volatilities

• Time delay module
  • Takes into account mines licensing
  • Delays decision taking
  • More realistic model behaviour

• Global uranium bank
  • Supply NU as last available resort and increases supply security

• Rules engine
Methodology

- Rules engine
  - Allows to define challenges in a regional, country or firm level
  - Allows simulate and measure policy effect on a global U market clearing price
  - Collect statistical data and use in calculations
Main decision making strategy based on a simple market rules
Mines act like an independent agents
Develop own strategy
Compete with other mines
The Global uranium bank

The global uranium bank algorithm
### Test case

<table>
<thead>
<tr>
<th>U mine</th>
<th>Total Reserves &amp; Resources tU</th>
<th>Reference Annual Extraction Rate tU/year</th>
<th>Year Available</th>
<th>Reference Cost $/kg U</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>150,000</td>
<td>15,000</td>
<td>2009</td>
<td>75</td>
</tr>
<tr>
<td>B</td>
<td>300,000</td>
<td>15,000</td>
<td>2009</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>200,000</td>
<td>20,000</td>
<td>2009</td>
<td>120</td>
</tr>
<tr>
<td>D</td>
<td>150,000</td>
<td>15,000</td>
<td>2018</td>
<td>60</td>
</tr>
<tr>
<td>E</td>
<td>10,000,000</td>
<td>26,000</td>
<td>2009</td>
<td>50</td>
</tr>
</tbody>
</table>

- Different P and Q coefficients
- Changing the slope of supply curve
- Each next produced unit will cost more
Test case results

Amount supplied per period with coefficients $Q=0.7$, $P=0.5$
Test case results

U market clearing price

Reference model market clearing price
Conclusions

• The impact of retained earnings proved to be insignificant
• The decisions were based upon the economic theory of individual firms
• Regional level rules engine proved significant effect on a U market price
Thanks for attention!

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