A System Dynamics Study of the Uranium Market and the Nuclear Fuel Cycle

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Project overview

Objective: Simulate the nuclear fuel cycle and uranium price for a range of scenarios for the time period 1988-2048 in order to understand the dynamics of the market, particularly looking at its response to shocks.

Methodology: System dynamics (Vensim PLE) coupled with time series analysis, regression, and expert interviews.

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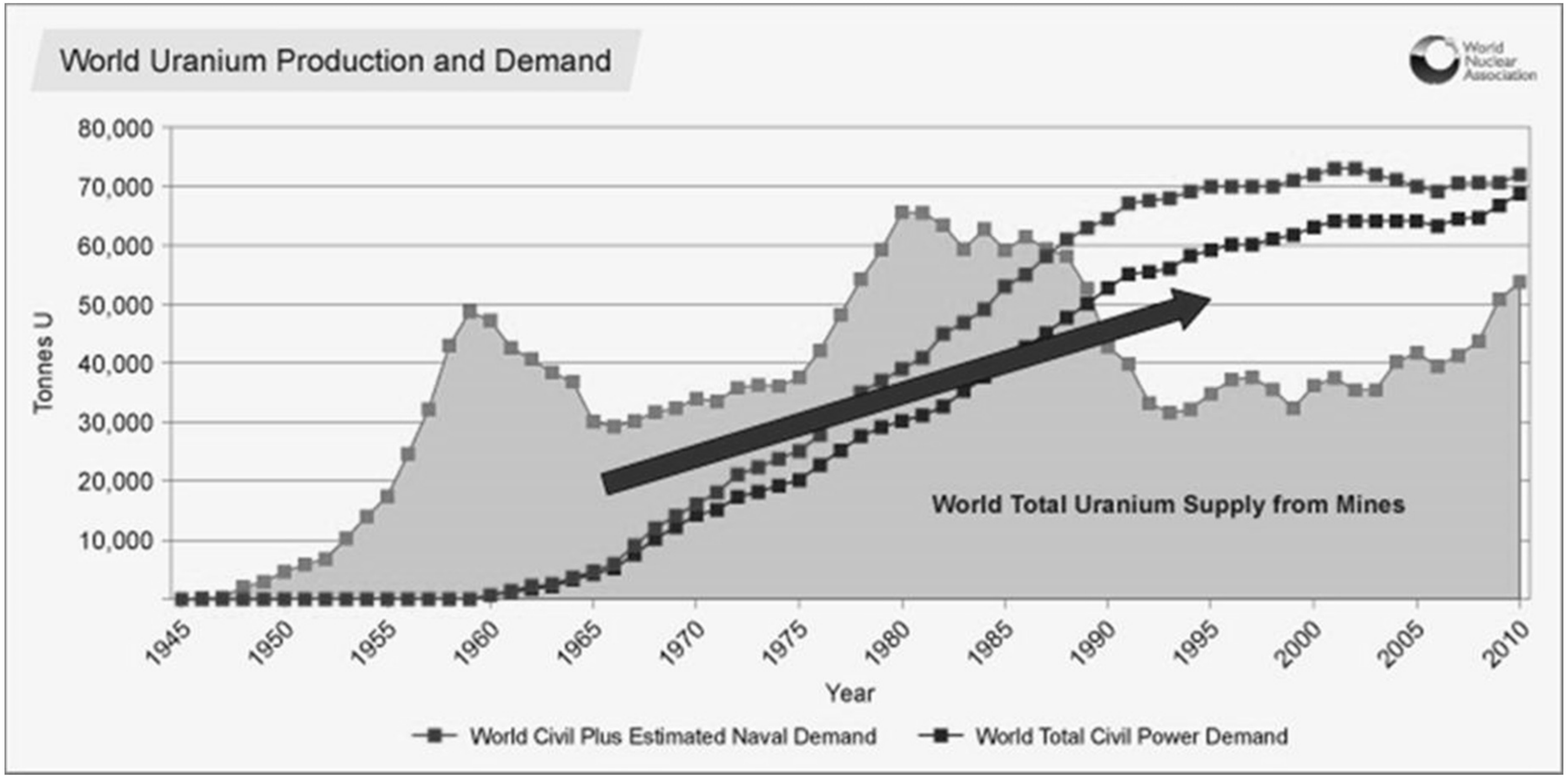
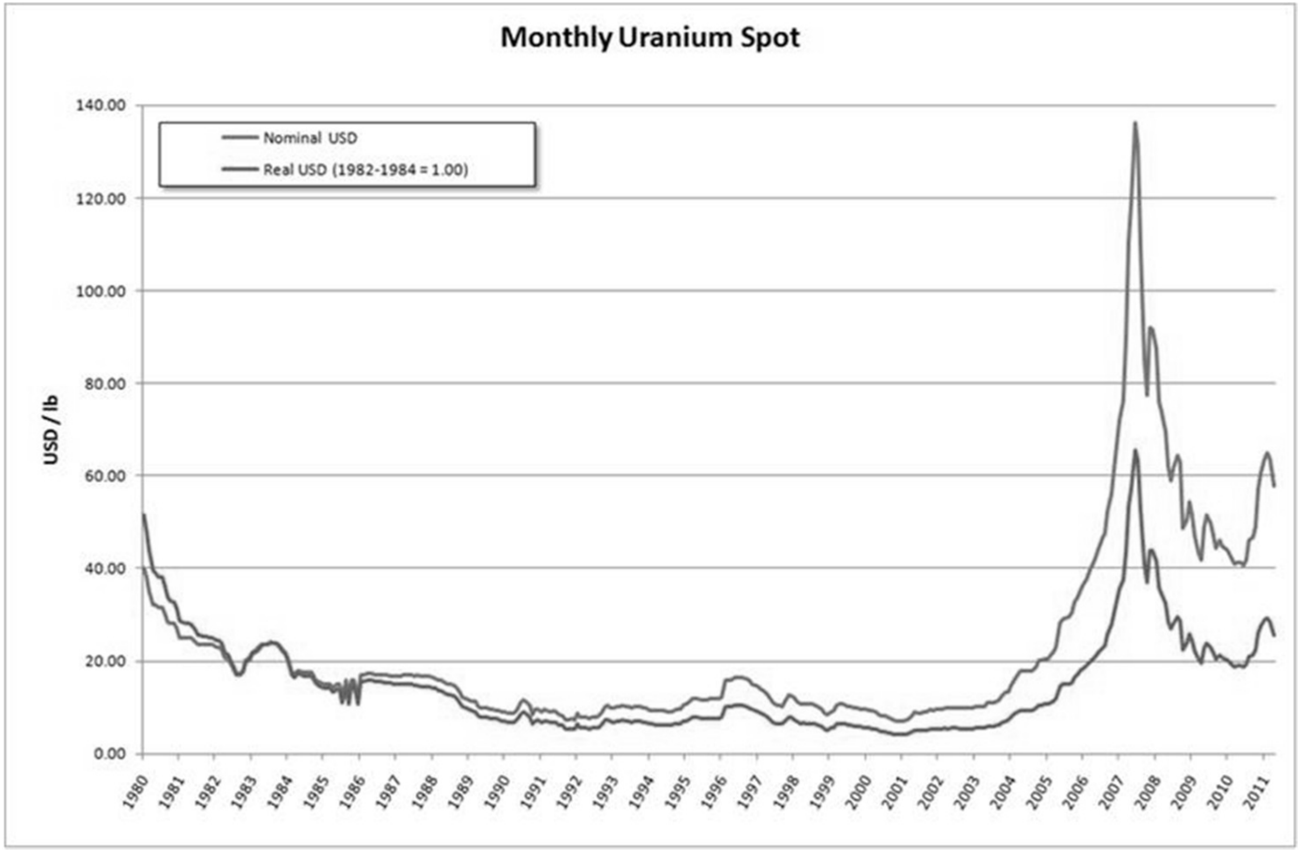
Rationale



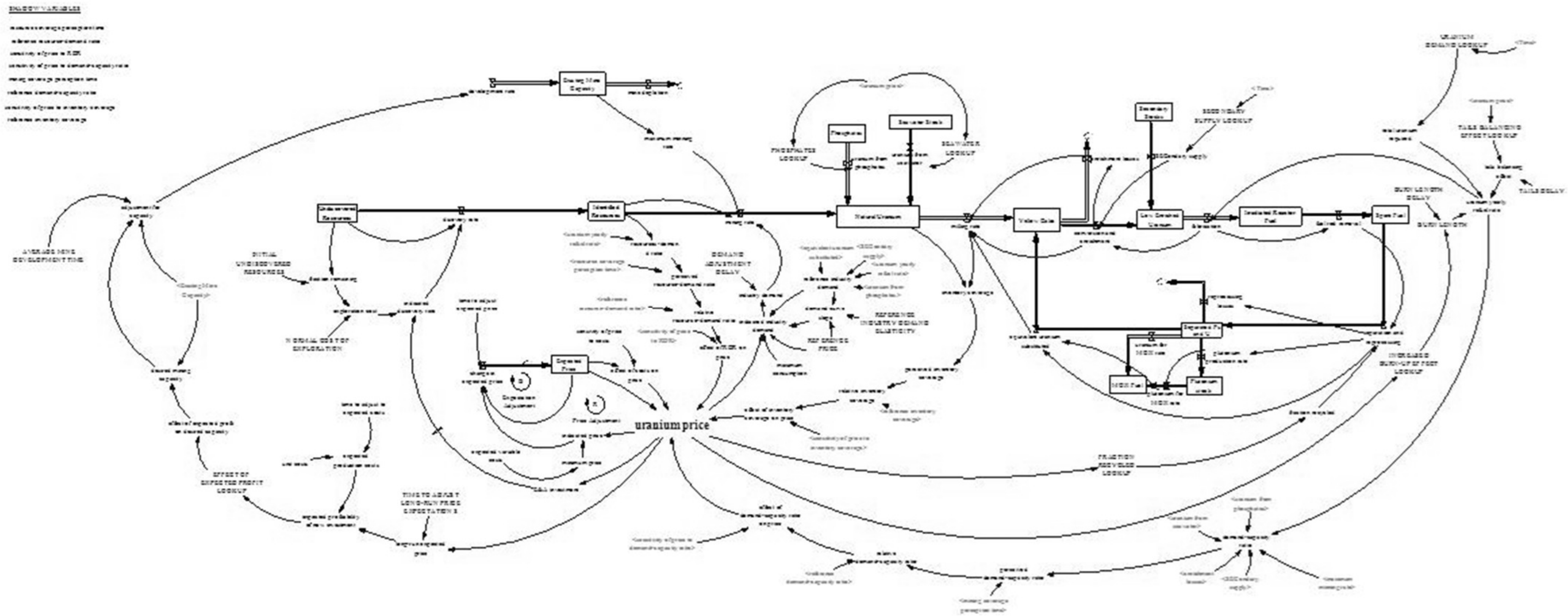
Graph from World Nuclear Association [http://www.world-nuclear.org/info/inf23.html]

Uranium price spike of late 2000s

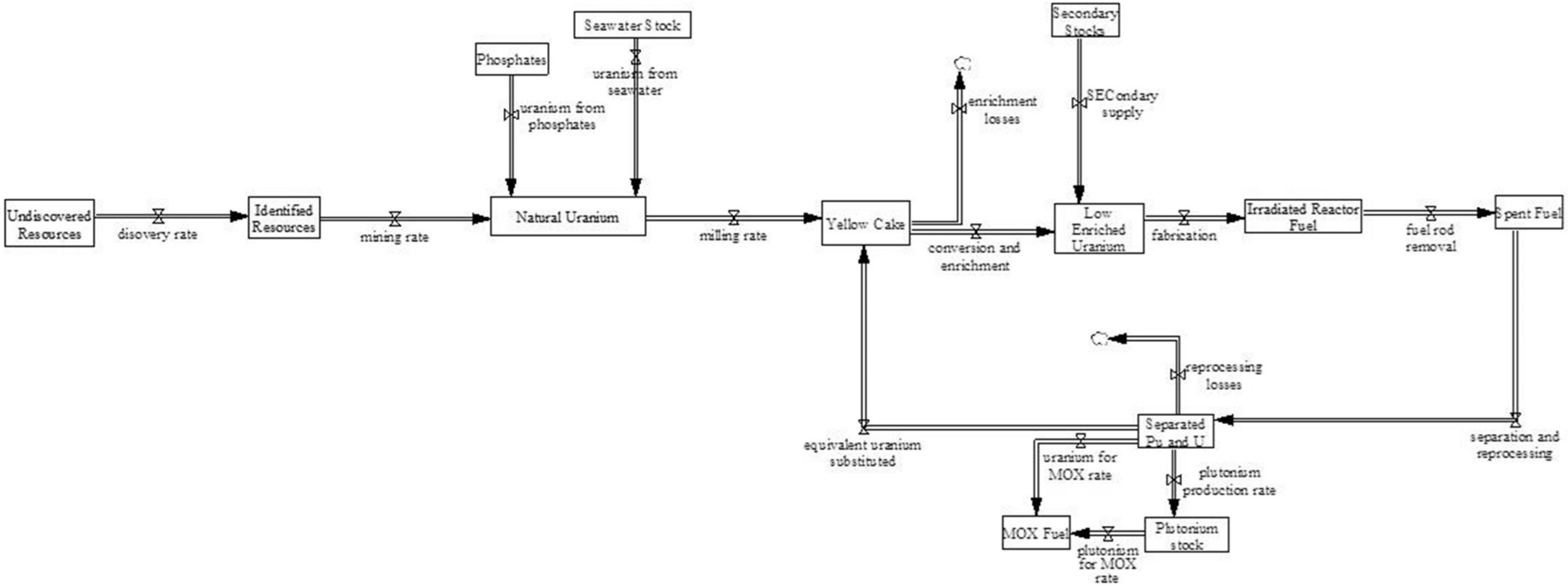


Graph: Intersect Insight [http://www.intersectinsight.com/2012/03/uranium-prices-to-firm-up-in-2013/]

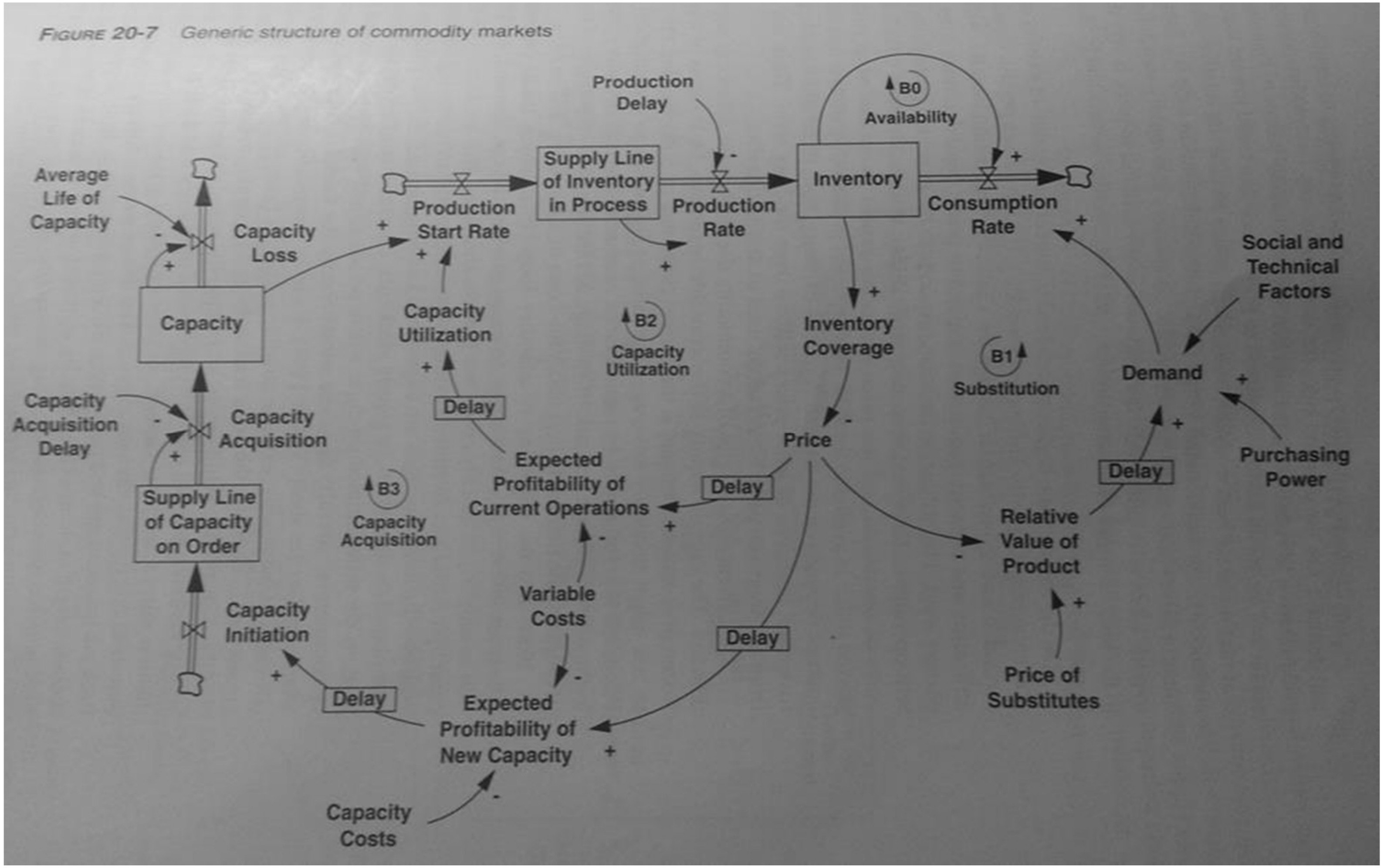
Full system dynamics model



Uranium stocks and flows



Based on: (a) Generic commodities model from Sterman (pp. 799)



Based on: (b) Naill's natural gas model

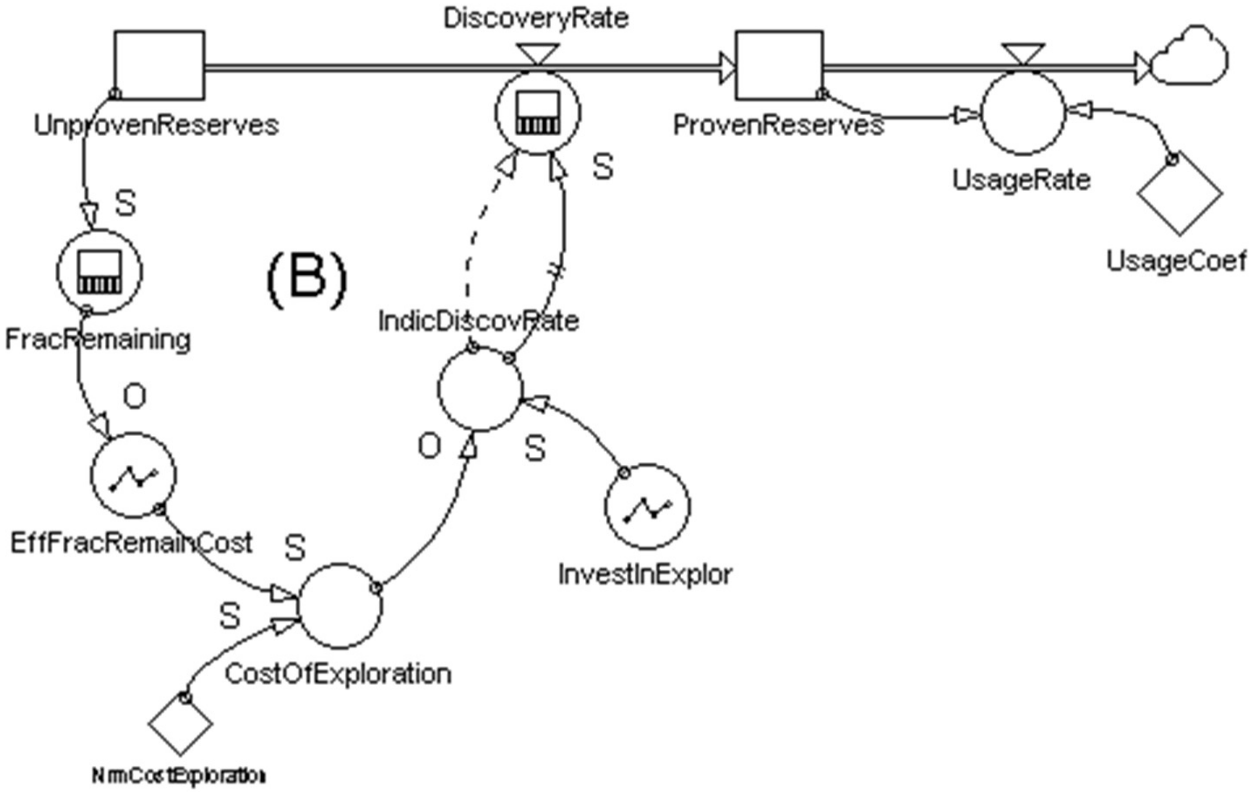
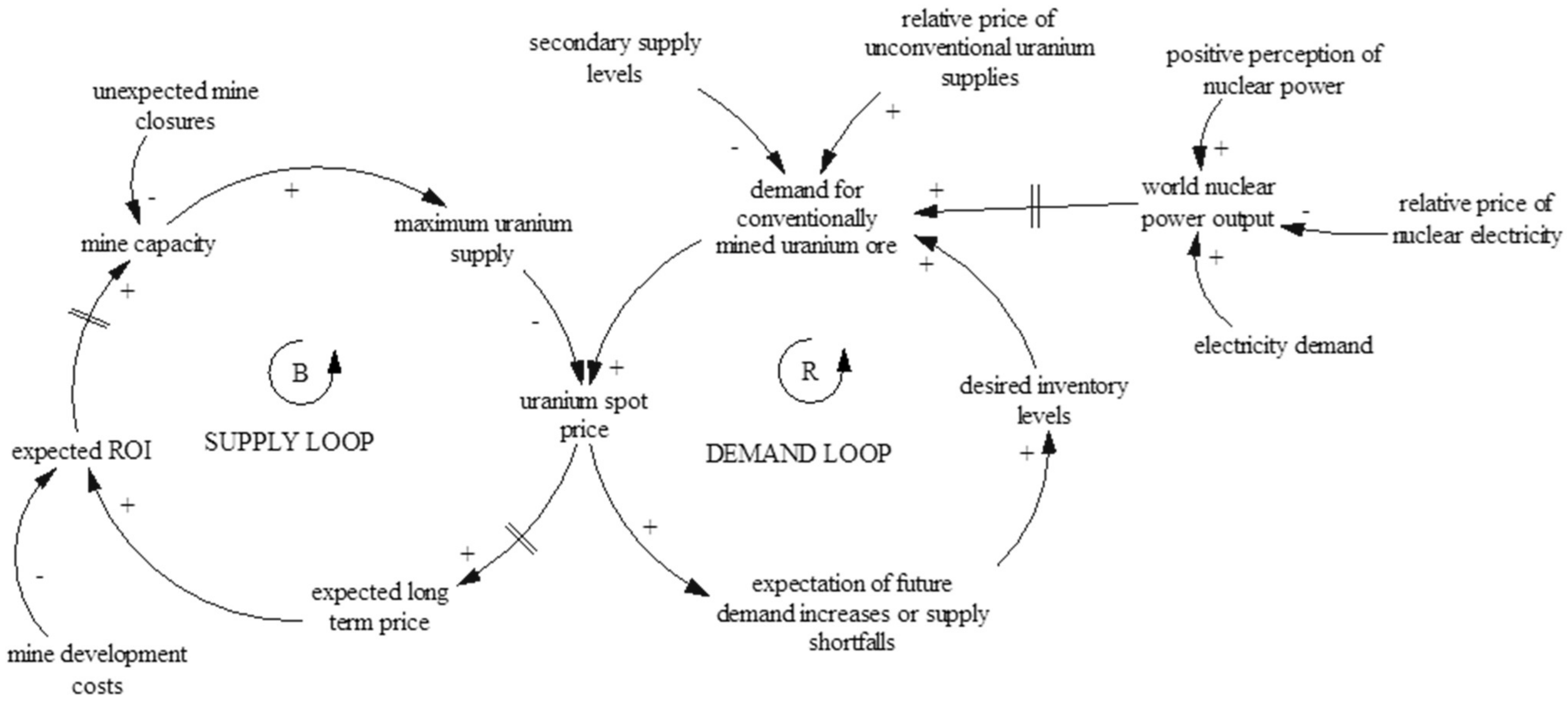


Image: http://www.systemdynamics.org/DL-IntroSysDyn/ch6_f.htm

Illustrative causal loop diagram



Price drivers

- **Ratio of demand to mine capacity**
- **Ratio of inventory coverage to desired inventory levels**
- **Ratio of demand to identified uranium resources**

Amplified by traders' short term price expectations

IAEA Demand scenarios

Country Group	2010			2020			2030			2050 (a)		
	Total Elect. TWh	Nuclear		Total Elect. TWh	Nuclear		Total Elect. TWh	Nuclear		Total Elect. TWh	Nuclear	
		TWh	%		TWh	%		TWh	%		TWh	%
North America	4687	892.6	19.0	5017	939	18.7	5262	875	16.6	5809	967	16.6
				5054	994	19.7	5382	1171	21.8		1612	27.7
Latin America	1206	26.2	2.2	1932	48	2.5	3220	70	2.2	6820	121	1.8
				2138	48	2.2	4835	144	3.0		484	7.1
Western Europe	3050	811.7	26.6	3540	692	19.6	4015	658	16.4	5851	484	8.3
				3728	935	25.1	4781	1109	23.2		1370	23.4
Eastern Europe	1821	330.6	18.2	2255	491	21.8	2664	646	24.2	3857	645	16.7
				2348	594	25.3	3235	853	26.4		1128	29.3
Africa	642	12.9	2.0	1278	13	1.0	2499	39	1.6	9314	81	0.9
				1534	13	0.9	3593	126	3.5		383	4.1
Middle East and South Asia	1654	23.0	1.4	2246	91	4.1	4949	238	4.8	18080	403	2.2
				2967	153	5.1	6127	417	6.8		1128	6.2
South East Asia and the Pacific	750			1025			1630	0	0.0	4317	40	0.9
				1074			1893	47	2.5		161	3.7
Far East	5732	533.0	9.3	6985	965	13.8	9210	1420	15.4	18971	1773	9.3
				8262	1218	14.7	12209	2009	16.5		3627	19.1
World Total Low Estimate	**19542**	**2630.0**	**13.5**	**24279**	**3240**	**13.3**	**33449**	**3946**	**11.8**	**73021**	**4513**	**6.2**
World Total High Estimate				**27104**	**3955**	**14.6**	**42056**	**5878**	**14.0**		**9893**	**13.5**

Notes:

(*) The nuclear generation data presented in this table and the nuclear capacity data presented in Table 3 cannot be used to calculate average annual capacity factors for nuclear plants, as Table 3 presents year-end capacity and not the effective capacity average over the year.

(a) Projection figures for total electricity generation are the arithmetic average between low and high estimates.

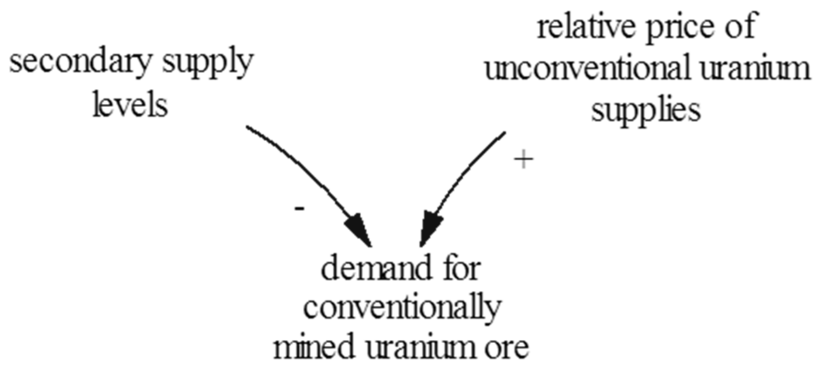
Data sources

- Primarily OECD/NEA Red Book (both the "retrospective" and the 2009 version).
- World Nuclear Association and IAEA, but also citing relevant journals and experts as necessary.
- Expert interviews: Ideally using Delphi Method, but time limitations prevented this.

Potential secondary supplies

Included:

- **Downblending of HEU from nuclear weapons**
- **Drawdown of stockpiles**
- **Uranium as a by-product of phosphates production**
- **Uranium from seawater**



Excluded:

- **Uranium from coal ash or carbon sequestration**
- **Uranium “cleaned” from other metals**

Potential demand reduction strategies

Included

- **Balancing of tails assays and enrichment level**
- **Recycling and reprocessing**
- **High burn-up fuel innovation**

Excluded

- **Fast reactors or fusion**
- **Thorium**
- **Higher load factor**

Delays

- Average mine development time (8 years)
- Uranium from phosphates delay (10 years)
- Uranium from seawater delay (10 years)
- Recycling delay (10 years)
- Increased burn-up innovation delay (10 years)
- Uranium discovery delay (1 years)

Potential shocks to the industry

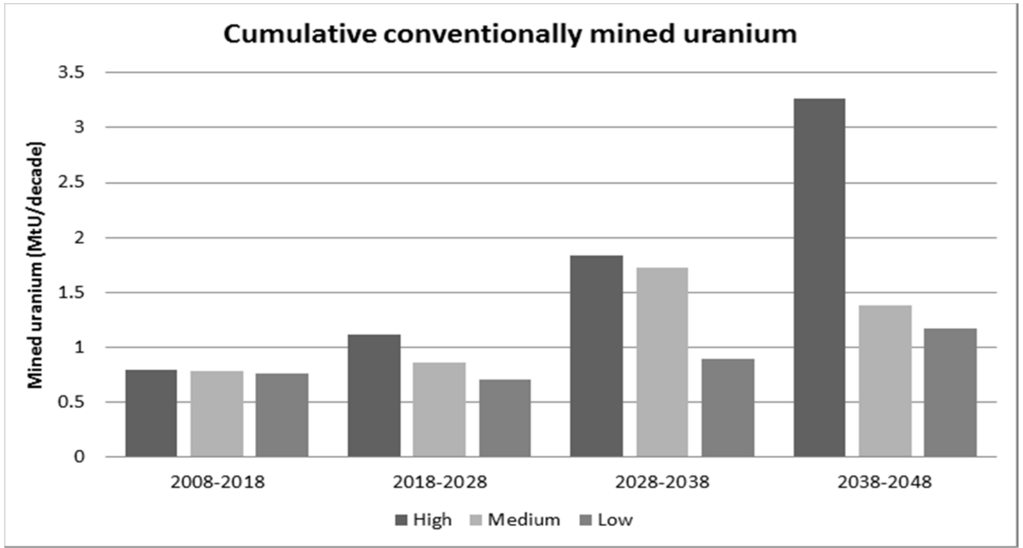
Scenario 1: Major fall in supply

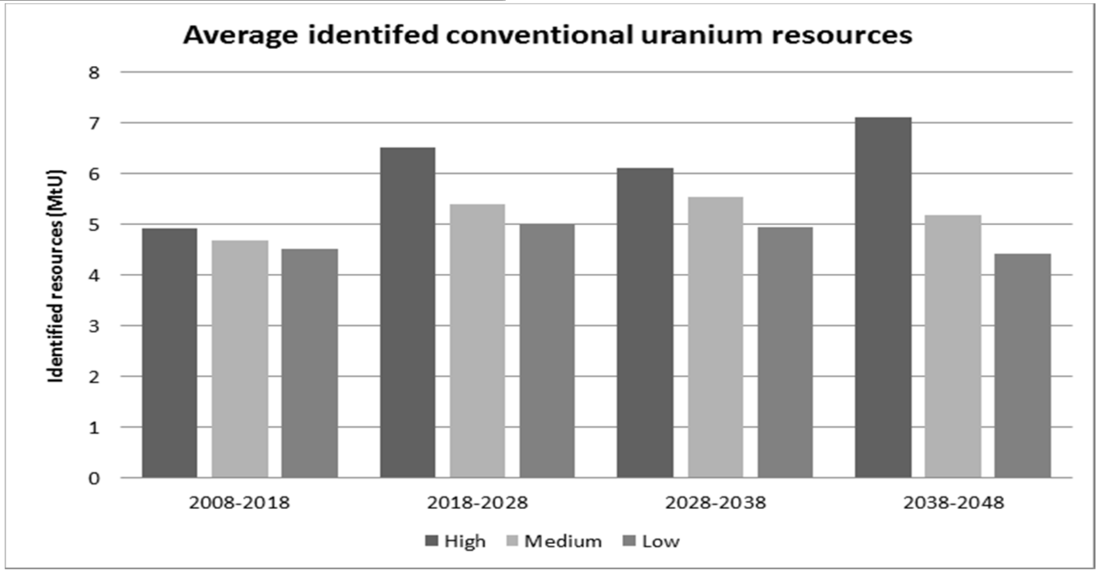
(a) Mine or country stopping production due to accident or political strife.
(b) US-Russia weapons down-blending agreement coming to an abrupt end.

Scenario 2: Major fall in demand

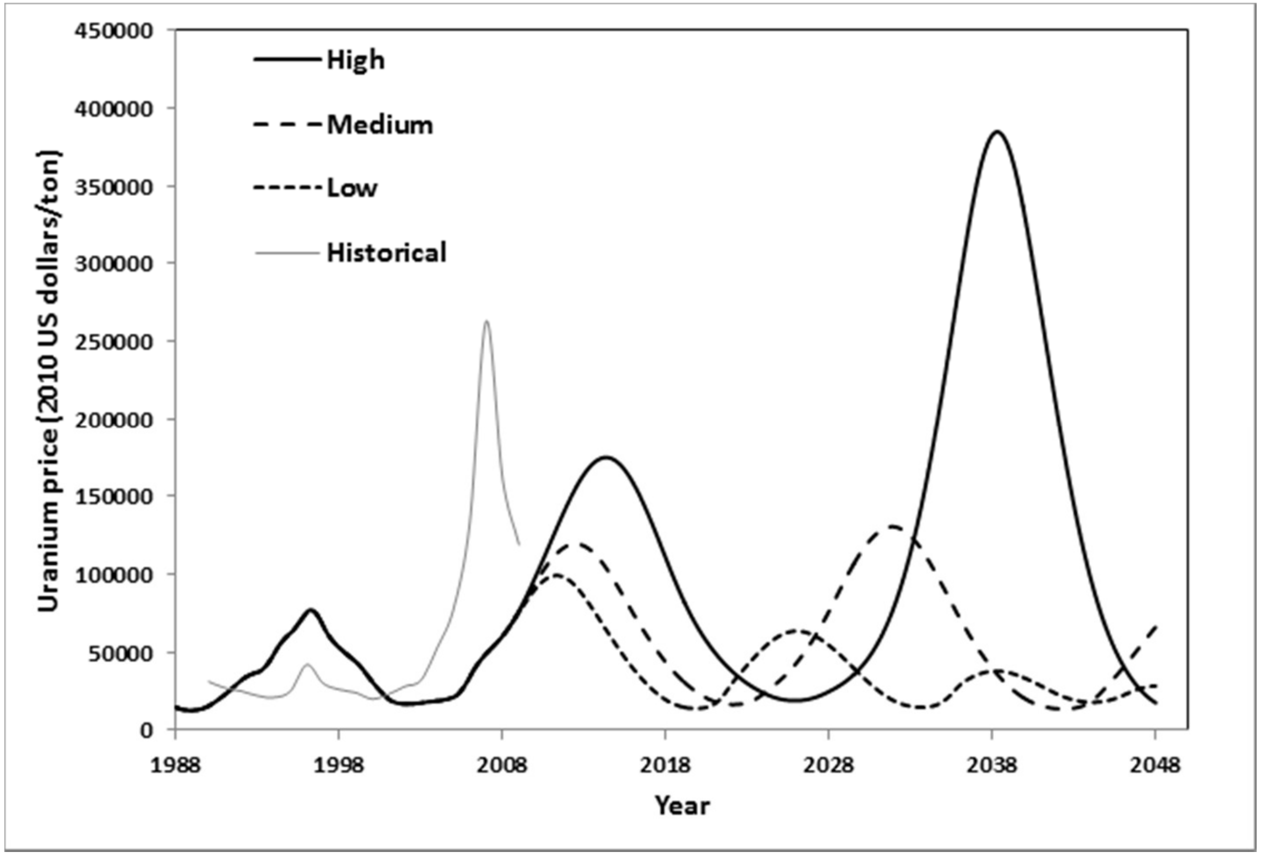
(a) Large country stops nuclear power production.
(b) Innovation in the area of fuel efficiency.

Resource discovery

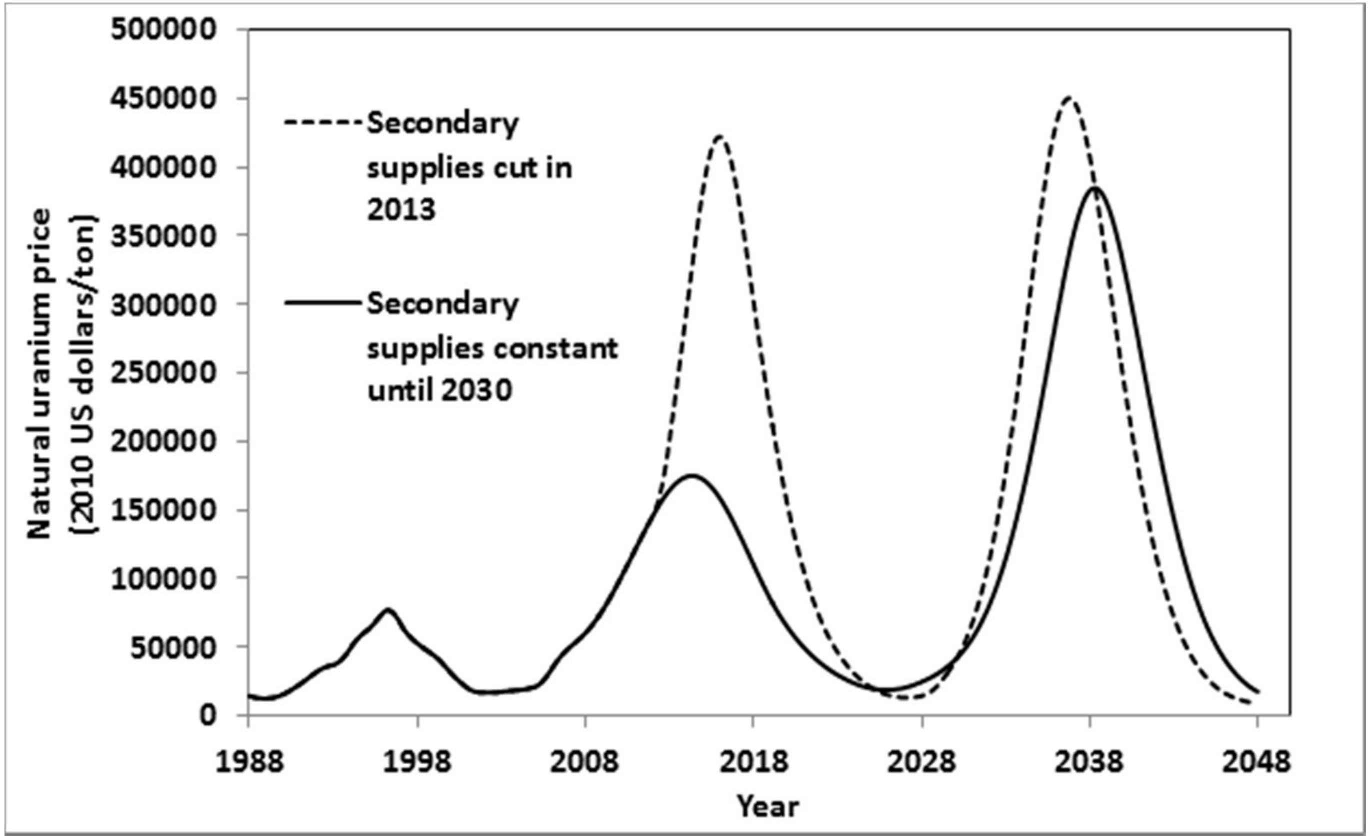




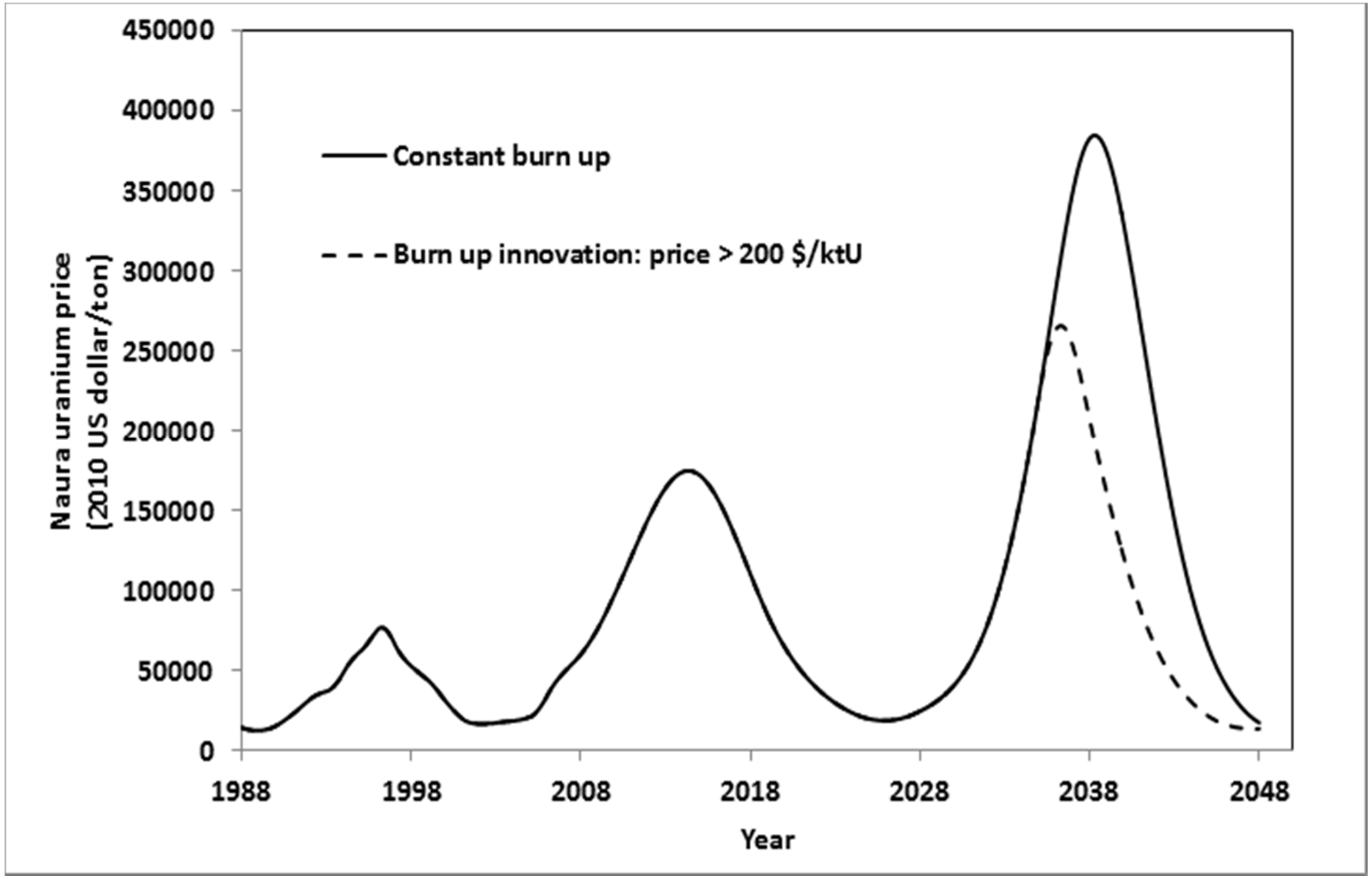
Base case – comparison with historical spot price



Scenario: US-Russia agreement abruptly ends



Scenario: High burn-up fuel innovation



Sensitivity analysis – importance of time delays

	% change of max. uranium price given	
	25% increase	25% decrease
Mine development time	689	-64
Time to adjust short-run expected price	-12	378
Elasticity of uranium demand	-42	30
Resource-demand ratio	16	-16
Inventory coverage ratio	14	-15
Demand-capacity ratio	-15	13
Time to adjust long-run expected price	-2	-2

Project conclusions

- **System dynamics is a useful tool for studying the nuclear fuel cycle.**
- **Resource scarcity should not be a problem before 2050.**
- **Uranium price is highly sensitive to supply side shocks and the length of time taken to bring new production online. *Time constants are very important.***