A System Dynamics Study of Uranium and the Nuclear Fuel Cycle

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May 2013

CWPE 1319 & EPRG 1311

UNIVERSITY OF CAMBRIDGE | Energy Policy Research Group

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EPRG Working Paper 1311

Cambridge Working Paper in Economics 1319

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Abstract To advance current knowledge of the uranium market, a system dynamics model of the nuclear fuel cycle for the time period 1988 to 2048 has been developed. The proposed framework of analysis illustrates some of the key features of the market for this commodity, including the role that time lags play in the formation of price volatility. Various demand reduction and substitution strategies and technologies are explored, and potential external shocks are simulated to investigate how price and the associated industry respond. Sensitivity analysis performed by considering key model parameters indicates that the time constant related to the formation of traders' expectations of future market prices embedded in the proposed price discovery mechanism has a strong influence on both the amplitude and frequency of price peaks. One particularly interesting and timely scenario simulated is the possibility of the ending of the "Megatons to Megawatts" program, in which the USA agreed to buy down-blended uranium from former Soviet nuclear warheads for use in power production. This agreement has not been formally renewed and we find that in the absence of new substitute sources this could cause a significant rise in uranium prices. Finally, our analysis leads us to believe that uranium resource scarcity will not pose any significant challenges until the second half of the twenty first century at the earliest, even if high uranium demand projections are realized.

Keywords System dynamics, uranium mining, nuclear fuel cycle, uranium market dynamics, sensitivity analysis.

JEL Classification

Contact	mr552@cam.ac.uk
Publication	May 2013
Financial Support	MPhil and PhD funding for Matthew Rooney by AREVA.

A System Dynamics Study of Uranium and the Nuclear Fuel Cycle

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1. Introduction

Demand for mined uranium ore is rising. Despite the negative effect on demand precipitated by the Fukushima disaster, the International Atomic Energy Agency (IAEA) [2011] project that installed nuclear capacity will increase, even in their pessimistic scenario for new reactor build. The demand for freshly mined uranium is put under further pressure by the fact that various secondary supplies, from down-blended nuclear weapons and stockpiles, are likely to due to decline as a share of world supply.

The sustainability of uranium as a fuel source is therefore a pertinent topic for study and it has come under scrutiny in recent years [Massachusetts Institute of Technology (MIT), 2010; Mathews and Driscoll, 2010; Dittmar, 2011; Zittel and Schindler, 2006] as nations plan for a world of rising electricity consumption. The merits or otherwise of nuclear power are not under consideration here, as it is clear that in all scenarios it will continue to form a substantial part of our energy mix for many decades to come – so the important question for the industry is whether resources are sufficient to meet long-term demand and whether the mining and fuel management sectors are agile enough to respond to short-term shocks that might generate extreme price volatility.

A model has been build using system dynamics software to study the uranium market and nuclear fuel cycle. System dynamics is a mathematical technique used to study complex systems that are not analytically solvable. Models are typically comprised of stocks, flows and feedback loops. It is a well-established tool for modelling and performance assessment of energy policy and resource dynamics [Cai *et al*, 2010; Kiani *et al*, 2010; Naill, 1973, 1992; Chyong *et al*, 2009, Silva *et al*, 2010]. We present results derived using this system dynamics model over a time horizon from 1988 to 2048. This long time horizon is necessary due to the fact that reactors and uranium mines can often take a decade to commission and build. We initiated the simulations in 1988 in order to benchmark them against historical data during the intervening period.

The objective in building the model is not to predict the future with certainty, but to study the behaviour of the pertinent market, evaluate its performance by emphasizing the endogenous structural perspective that is the cornerstone of the system dynamics tradition, as well as identify a range of outcomes, trends and possible market developments in response to external shocks or policy interventions. We also examine the key determinants of the uranium spot price through sensitivity analyses involving key model inputs.

The basic nuclear fuel cycle under consideration is given in Figure 1. For clarity the complicated structure of auxiliary variables has been removed. However, the complete structure is included in Appendix 1. Uranium stocks are represented by boxes, whilst the flows of material and system losses are represented by arrows. The main horizontal flow of material through the centre shows how the uranium ore goes through the processes of discovery, mining, milling, conversion, enrichment and finally fuel fabrication. After typically spending approximately three in years a reactor the spent fuel is removed and stored for later disposal or reprocessing.

Once built, demand for nuclear power is extremely inelastic ("0.01% and statistically non-significant" according to Kahouli [2011]) and fuel costs make up a small fraction of the total costs (upfront capital costs making up the majority). Furthermore, the industry has a strong incentive to pay higher prices in the event of constrained supplies. For this reason, the total World uranium required is treated as exogenous and various demand scenarios are examined. The demand for freshly mined uranium is, however, somewhat removed from, and much more volatile than reactor requirements. Price movements in the short term can be large and due to changes in perception of security of supply or, for example, predictions of a new worldwide expansion of nuclear power (even though new reactors take a decade to bring online). In light of the above, the model focusses mostly on the uranium mining sector and simulates what fraction of uranium demand will be met through traditional mining, stockpile drawdown, unconventional supplies, and also reprocessed and recycled spent fuel.

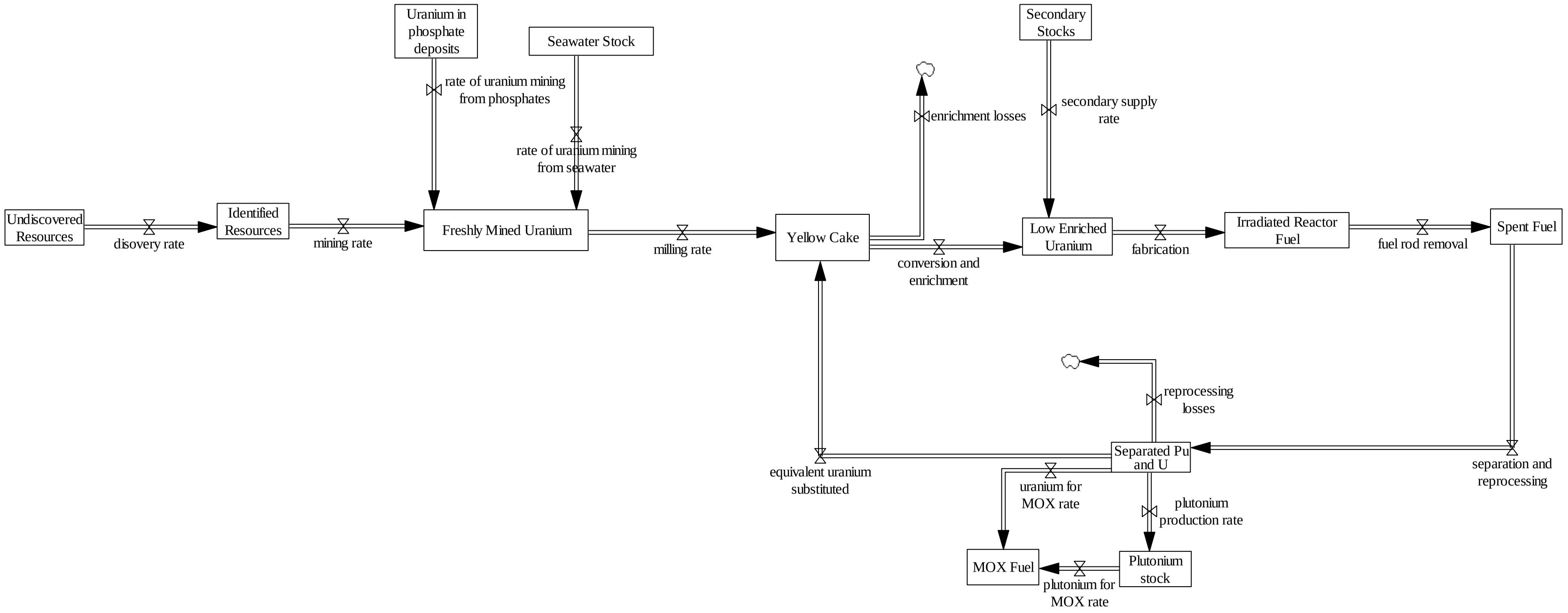

Figure 1: Schematic diagram showing the flow of uranium through the nuclear fuel cycle

Based on expert interviews (see Appendix 2) and examination of the relevant literature, a determination of the most likely substitution and demand reduction techniques was made. In the event of sustained high uranium prices (there are different price triggers and associated delays for each alternative), the following resources become economically viable and begin to be exploited:

- Uranium as a by-product of phosphates production. This is a proven technique that was used in previous decades, but, as it is by-product production, there is a limit to what can be produced in this way [IAEA, 1989 as quoted by World Information Service on Energy (WISE) Uranium Project, 2012].
- Recycling and reprocessing. This is assumed to continue at the current rate and expand slowly given sustained high prices. Changing a fuel cycle from open to closed is a decision taken at the level of national governments and would take many years to implement.
- Uranium from seawater. This is potentially a huge reserve, but it is unlikely to be scaled up unless prices increase substantially and remain high for many years, with the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD-NEA) and the International Atomic Energy Agency (IAEA) estimating a price of at least 300 dollars per tonne of natural uranium ($/tU) is necessary [OECD-NEA and IAEA, 2004]. In the model it acts as a "soft cap" on prices, only becoming significant when prices remain above $300t/U for many years.
- Tails balancing effect. Uranium 235, the isotope required for nuclear fuel, is typically mined from rock in which it is found in concentrations of less than 0.4%. For fission to occur in a reactor it must go through a process of enrichment to increase its concentration to between 3.5 and 5% [World Nuclear Association, 2009]. Enriching to 5% incurs more enrichment costs but makes more efficient use of the natural uranium resource. Enriching to 3.5% saves some enrichment costs but does not make the most of the mined uranium. In periods of high uranium prices relative to enrichment prices, therefore, uranium 235 is enriched to a higher level (and vice versa). The tails assay refers to the waste stream created during the conversion and enrichment process, which contains low levels of uranium 235.

It should be pointed out that secondary stocks, in the form of inventories and down-blended nuclear weapons, make up a significant fraction of world supply. However, they can be treated as exogenous due to the fact that they are more influenced by Government action than by the market price of uranium.

Excluded completely from consideration are 4th generation[1] fission reactors and nuclear fusion. Given that the model runs until only 2048, along with the fact that it can take more

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[1] Reactors can be generally classified into four generations: Gen-I comprised prototype reactors built in the1950s; Gen II developed from these prototypes and were built from the 1960s-1980s. Most operational reactors are Gen II. Gen III, the latest generation of operational reactors. Gen III+ designs evolved from Gen III (any new nuclear power plants in the UK would be of this type). Gen IV are advanced reactor designs expected to be available for construction beyond 2030 [Parliamentary Office of Science and Technology, 2008].

than a decade to design, commission and build a new reactor, even if these concepts are proven by 2030, it is extremely unlikely that either of these innovations could have a significant effect on uranium demand in this timescale. One scenario that is examined, however, is the potential for an innovation to take place in the area of fuel cladding that would allow for much greater specific energy extraction from uranium, thus suppressing demand, whilst still using the existing fleet of 3rd generation light water reactors.

2 Theoretical background and proposed methodological approach

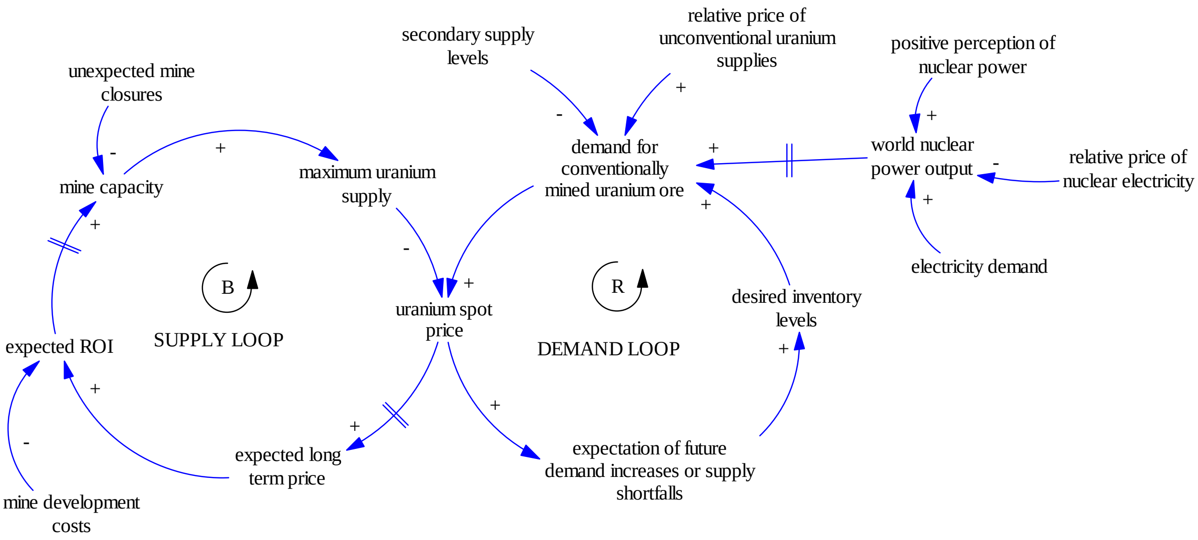

Figure 2: Causal loop diagram indicating the theory behind price formation in the system dynamics model.

The system dynamics model draws on the structure of the generic commodities model outlined in *Business Dynamics* [Sterman, 2000], though it has been adapted specifically for the uranium market. In addition, it includes a resource discovery loop similar to that put forward by Naill [1973] in his natural gas model. This integration of resource discovery within a uranium market model using system dynamics to enable endogenous price discovery represents, to the best of our knowledge, the first such result in the pertinent body of literature.

Most natural uranium is sold via long-term contracts between mining companies and utilities. These contracts are usually confidential so it is difficult to get an up-to-date view of the total uranium market. About 15%, however, is sold on the spot market and these prices are published daily on websites such as TradeTech [www.uranium.info]. The contract price will be most influenced by the production price of natural uranium and the long term supply-demand balance. The spot price will be more influenced by shorter term mining capacity-demand balance and can also be artificially inflated or depressed by speculation. However, spot market prices are relevant to contract prices as it is typical in the industry to have "price escalation clauses" in contracts that link to the spot price in some way [AREVA, 2012, pp. 132]. The model created for this study derives the spot price endogenously through the influence of various factors that are explained below. The behaviour of the spot price and the underlying fundamentals of the market are then used to determine longer term price expectations that influence mine capacity investment decisions by companies.

The key determinants of the uranium price are represented in the form of a casual loop diagram in Figure 2. Building the causal loop diagram is an intellectual exercise that enables the key variables and feedback loops to be identified. The variables directly related to one another are connected via arrows and the polarity (+ or -) indicates if a positive change initiates a positive or negative change in the following variable, and vice versa. Two perpendicular lines on the arrow indicate a significant delay in the system. It should be noted that this represents a simplification of the full system dynamics model comprised of only two loops: supply of freshly mined uranium and demand for freshly mined uranium. The various components of the causal loop diagram are thus explained:

Exogenous and semi-exogenous demand drivers

The long-term demand for nuclear power (and hence uranium) is extremely inelastic with respect to uranium price, so this is treated as an exogenous input to the model based on IAEA forecasts of nuclear electricity capacity [IAEA, 2011]. The other two sources influencing the demand for freshly mined uranium are associated with the following variables: 1) The relative price of unconventional uranium supplies, as well as the option to recycling and reprocess waste. As the uranium price increases, the relative attractiveness of unconventional uranium sources (phosphates, seawater) and uranium recycling rise and as these alternative production methods come online demand for mined ore becomes suppressed. Higher prices also incentivise the more efficient use of the uranium resources; 2) Secondary supplies from weapons down-blending and government inventories, which are likely to decrease over time. This will create a shortfall that will need to be met by an increase in primary production.

Demand loop

Short-term demand for mined uranium is much more volatile than nuclear power output, which is easily predicted from the reactors being commissioned and decommissioned. New power output is also typically reliable and predictable due to nuclear power being used as a base-load electricity supply in most cases. The average load factor for nuclear power stations has been close to 80% for many years [IAEA PRIS, 2012]. The main drivers of price in the short-term are traders' expectations and producers' desired inventory levels, which are linked to one another and illustrated by the demand loop in Figure 2. This aspect of the model acts to reinforce price rises and falls. If inventory temporarily falls beneath the desired level then prices rise to stimulate production and vice versa. A price expectation aspect to the model simulates the behaviour of speculators who invest when the underlying conditions suggest price rises are necessary and likely, and withdraw from the market when the opposite occurs, thus exacerbating the cyclical behaviour that is typical in commodity markets [Cashin and McDermott, 2002].

Supply loop

If mining companies expect uranium prices to exceed the cost of production in the future they will make a decision to invest in new capacity. If the supply-demand ratio falls rapidly, however, then the mining industry may not be able to bring new capacity online in time and so production will be constrained, inventories will be drawn down, and prices will rise. Only when new capacity is brought online, which can take years, will prices begin to fall again. These long delays involved in developing new mines are a key factor in the cyclical nature of commodity markets.

Other effects not included in causal loop diagram

Another effect on prices, not included in Figure 2, but included in the full model, is more long term and assumed in the model to have only a weak effect: the ratio of demand to identified resources. Higher uranium prices induce companies to explore for new reserves, which in turn increases the known uranium resource base and therefore produces a mild negative effect on price. This effect is likely to become relevant only in the event of severely depleted resources. Some researchers have predicted that uranium scarcity could become a problem by mid-century [Dittmar, 2011; Zittel and Schindler, 2006], but other authoritative sources on the topic maintain that uranium reserves will be sufficient to economically satisfy demand until at least 2050 [MIT, 2010; Matthews and Driscoll, 2010; IAEA, 2011].

One of the most important processes in building any system dynamics model is in specifying the model boundaries and thus the degree of aggregation [Sterman, 2000]. The following table summarises assumptions made with regard to the variables in the model that are endogenous, those deemed exogenous, and also the variables that were consciously excluded.

Cross-price elasticities can be important in the mining industry as various metals are often extracted together from the same mine. However, the majority of uranium mines are exclusively for extracting uranium, so cross-price elasticity would only have a small effect. Inflation and discounting are ignored because this is not a cash flow model. Prices are in constant (2010) dollars and investors are assumed to respond based on their forward expectations of uranium prices.

Endogenous	**Exogenous**	**Excluded**
Uranium resources	Uranium demand	Inflation and discounting
Uranium price	Secondary supply	Cross-price elasticities
Uranium discovery rate	Mine development time	
Mining rate	Mine development costs	
Uranium from phosphates	Ongoing production costs	
Recycling rate	Mine capacity shocks	
Uranium "burn" rate		
Tails balancing effect		

Table 1: Endogenous, exogenous and excluded variables.

3. Main results and discussion

3.1 Base case for high, medium and low demand scenarios

Figure 3 shows the simulated uranium spot price for the high, medium and low demand scenarios (based on IAEA [2011] projections). These results are for the model with no policy interventions or external shocks.

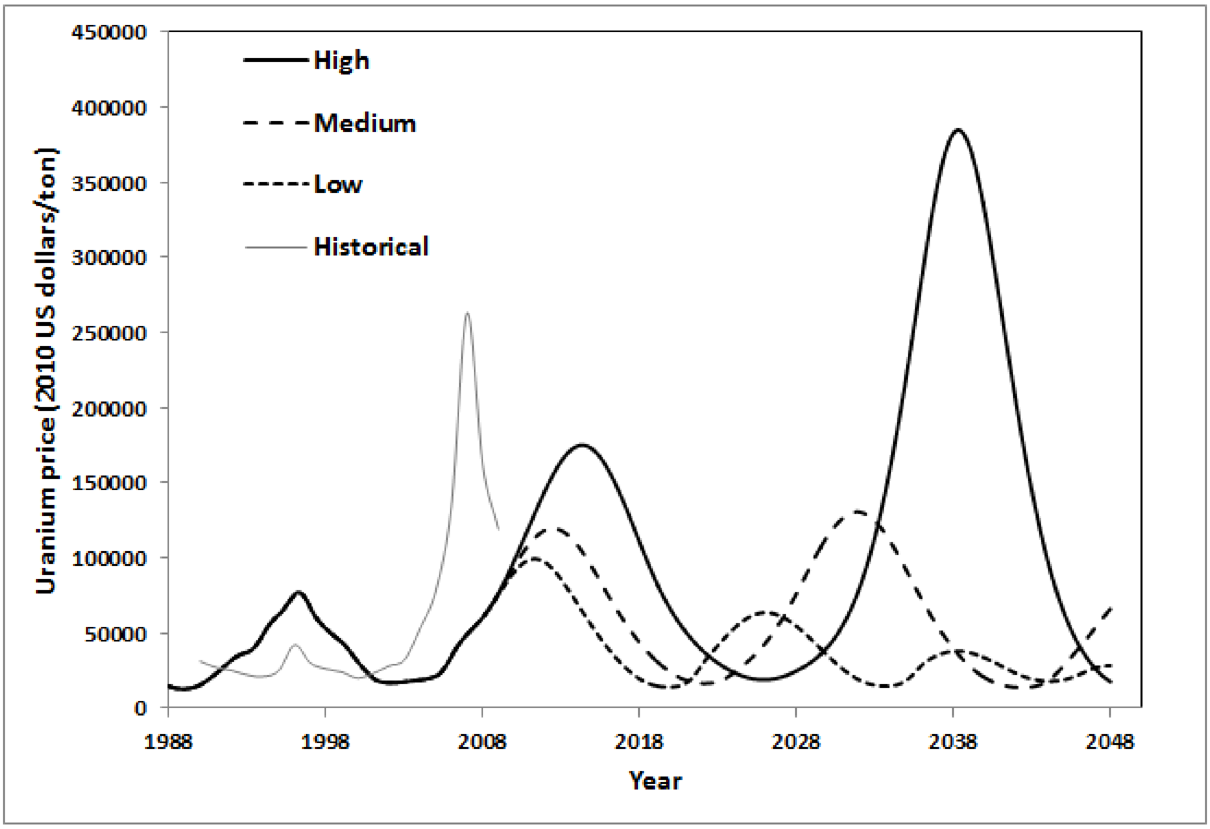

Figure 3: Uranium spot price – historical and simulated (high, medium and low demand scenarios).

The values of many variables in the model up to 2010 are known with a high degree of certainty, particularly relating to the uranium demand, mining rate and identified resources [OECD-NEA and IAEA, 2006; WNA, 2009, IAEA, 2011]. However, some of the more intangible variables cannot be directly measured. To take account for the uncertainty in these variables, a base value for each was set through a combination of expert interviews (see Appendix 2), a literature review and a comparison with historical data, and then a sensitivity analysis was conducted to determine the most influential factors in the model. The results of the sensitivity analysis are discussed below in Section 3.2.

3.2 Sensitivity analyses and discussion of key variables

To determine the sensitivity of uranium spot price to the uncertain variables in the model, each one was individually increased by 25% from its base value and then decreased by 25% to see what effect this would have on the maximum uranium price in the 1988-2048 period, as calculated by the system dynamics model. Table 2 shows the results of the sensitivity analysis of key parameters in the model. One immediately notices that the two most influential variables are “Time to adjust short-run expected price” and “Mine development time”. These can be analysed separately.

	% 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

Table 2: A summary of the main sensitivity tests conducted. These data reveal the importance, in particular, of the average time to develop a new mine and of the informational delay relating to traders forming their opinions of future prices.

The price expectation loop relates to the expectations of commodities traders and price movements up or down change expectations, which in turn have a reinforcing effect on price dynamics. Even though intuitively one might think this time constant[2] to be short, expectations of traders with experience in the industry can actually take a year or more to be solidly formed. Indeed, traders learn to ignore short term noise and focus on the underlying conditions [Sterman, 2000, pp. 818]. The results in Table 2 suggest that the impulsiveness or otherwise of uranium traders in the formation of future price expectations represents one of the key factors that influence the price volatility observed in the uranium market (as intuitively expected) .

Figure 4 graphically illustrates the importance of the price discovery time constant. A reduction in the time constant of just 0.2 years (from 1.0) changes the frequency of price peaks and dramatically increases their amplitude. The identification of this time constant as the key informational delay in the model has important implications for the modelling of commodities markets using system dynamics and should be a focus of future research [Sterman, 2000].

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[2] In system dynamics, the time constant refers to a delay in changing between the current actual and the future desired state of the system once corrective action has been initiated [Sterman, 2000, pp. 276].

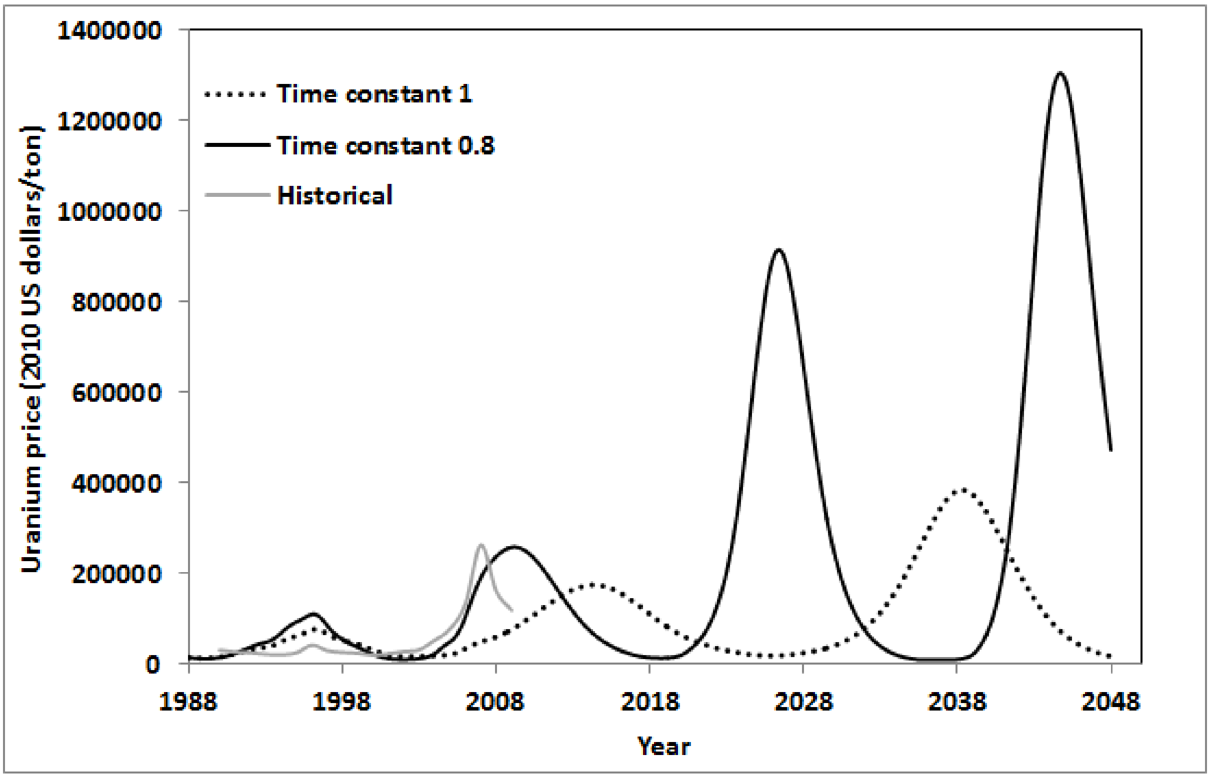

Figure 4: Comparison of price dynamics when the mine investment decision delay is 1 or 0.8, all other variables being held constant.

The other informational time constant in the model relates to the decision of a mining company to invest in new capacity ("Time to adjust long-run expected price"). Sensitivity analysis, however, suggests that this is much less important regarding price dynamic patterns. The observed uranium market resilience to the above investment decision can be attributed to the physical delay of actually constructing a new mine, which will likely be much longer – typically around eight years. As Table 2 shows, an increase of just two years in the average mine development time increases the highest price peak by 378%. In reality, there may be other balancing effects that partially mitigate this price rise, but this certainly emphasizes the need for forward planning and contingency in the uranium market to dampen such volatility.

3.3 Resource depletion

Though a contentious issue, studies in the USA [MIT, 2010; Matthews and Driscoll, 2010] have predicted that uranium scarcity will not be a problem until at least mid-century and our analysis agrees with this finding. The bar charts in figures 5 and 6 show the cumulative mined uranium in each decade preceding 2048 and the average identified resources during each of these decades. Results are presented for the high, medium and low demand scenarios.

Figures 5 and 6 show that in all scenarios the identified resources will be higher in 2048 than they are today. This result requires some reflection and clarification. The OECD place uranium resources into two categories: "identified resources" and "undiscovered resources" [OECD-NEA and IAEA, 2006, 2010]. The level of identified resources is known with a high degree of accuracy due to confirmation by measurements made in the field. The level of undiscovered resources is more speculative and its estimation is based on previous experience

[OECD-NEA and IAEA, 2010]. In the highest demand scenario prices are higher and this incentivizes exploration companies to look for potential new mines. Exploration generates new data resulting in an increase in confidence regarding the location of uranium reserves. As a result, in the proposed model, uranium flows from the undiscovered resources stock to identified resources.

The above conclusions rest on a number of assumptions, however. Firstly, there is an optimistic assumption that all the identified resources (based on the "speculative and prognosticated" reserves category in the 2009 "Red Book" [OECD-NEA and IAEA, 2010]), plus an additional amount based on countries that don't report this category, can be realised. But this assumption is also pessimistic in that it is not possible in the model for the "undiscovered resources" category to increase, which is likely in reality if significant exploration and appraisal activities take place in the future. Finally, these simulations are based on IAEA projections made early in 2011 and their demand scenarios have since been revised down slightly (~10%) due to the effects of the Fukushima disaster on the nuclear industry [IAEA, 2011, 2012].

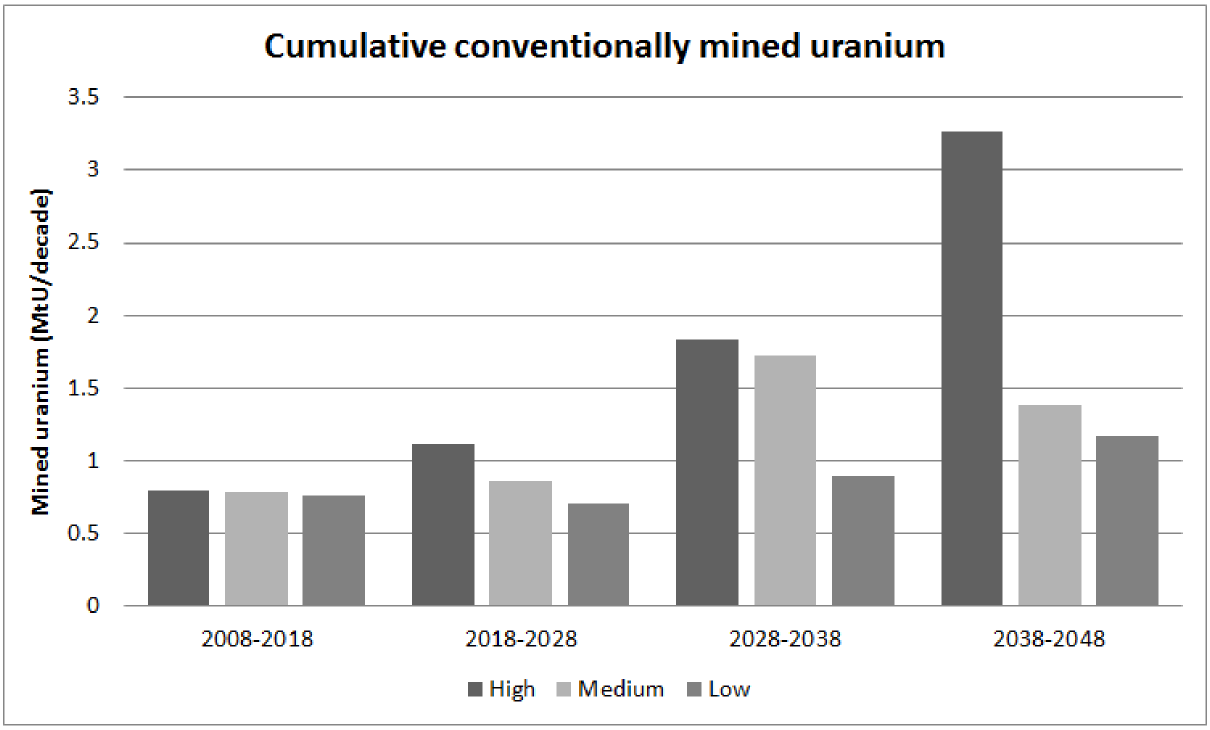

Figure 5: Bar chart showing the cumulative uranium mined in the decades preceding 2048 for the high, medium and low demand scenarios. Unsurprisingly, high demand scenarios are associated with higher extraction rates.

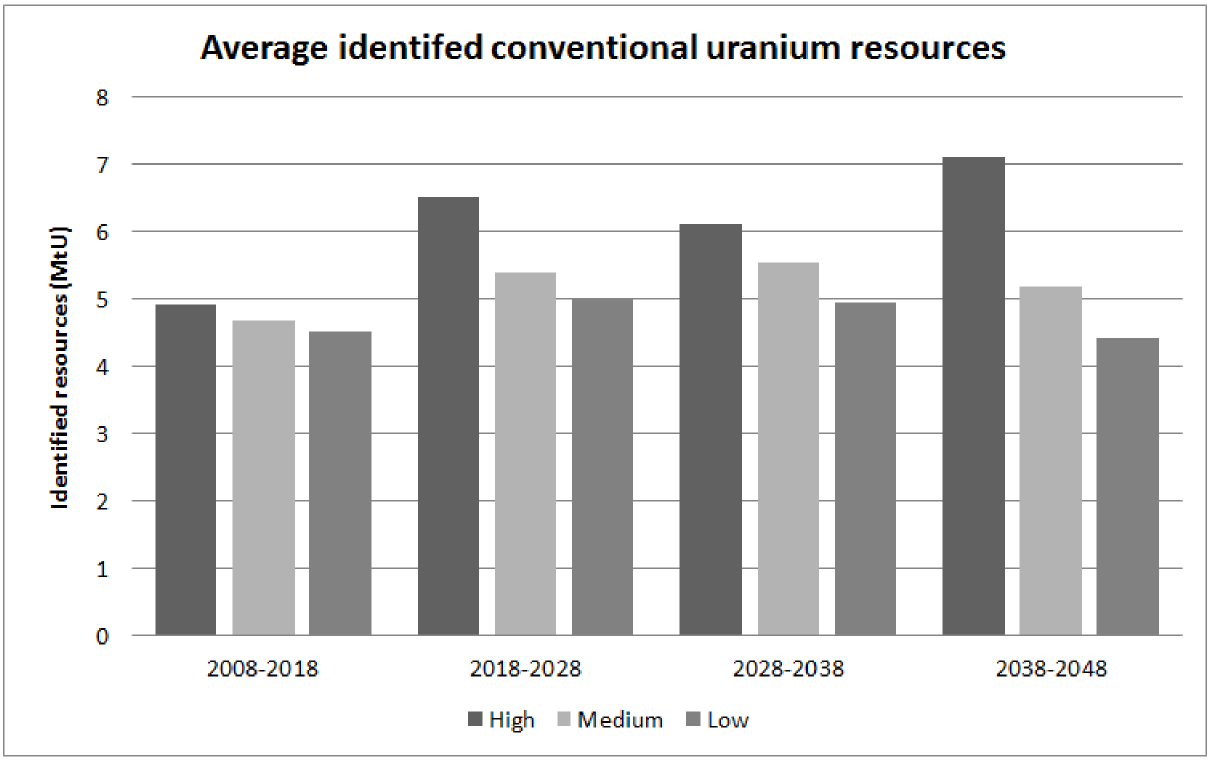

Figure 6: Bar chart showing the average identified uranium resources for the decades preceding 2048. The chart shows that in the high growth scenario, despite more uranium being used, more resources are found by mining companies due to higher price incentives.

3.4 Potential exogenous shocks and their effect on price

The primary objective in developing a system dynamics model for a complex system is rarely to accurately predict its future state, but rather to draw insights and enhance our understanding regarding its possible behaviour characteristics and performance outcomes by recognizing that they are jointly determined by endogenous/structural elements and certain policy options coupled with possible exogenous shocks. In our analysis of the uranium market, we conclude that it could be impacted in two main ways:

Scenario 1: Major fall in supply (supply shock). This eventuality could be due to a major mine or country stopping production due to accident or political strife. One such imminent scenario is the potential for the US-Russia weapons down-blending agreement [United States Enrichment Corporation, 2012] coming to an abrupt end. An agreement between the United States and Russia to down-blend highly enriched uranium (HEU) from Russian nuclear weapons for use in commercial power stations has been providing the largest secondary supply uranium in the past decade. This is due to expire in 2013, with the potential elimination of the majority of secondary supplies worldwide. It is not yet certain if the deal will be extended. Figure 7 shows the significant effect this could have, with a potential doubling of prices, though it is likely that the nuclear industry will have planned somewhat for this eventuality, which would ameliorate the price rise.

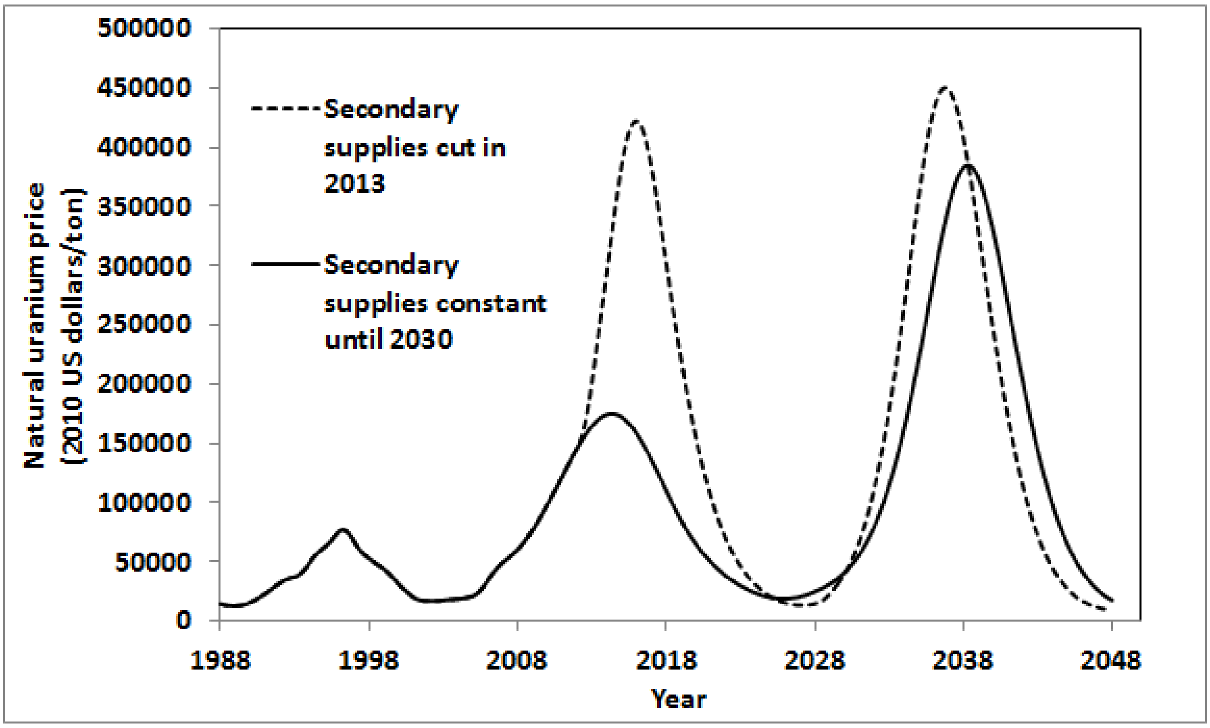

Figure 7: Effect of 10,000 tonne drop in secondary supplies at 2013. These data illustrate the short-term importance of the continuation of the "Megatons to Megawatts" program.

Scenario 2: Major fall in demand (demand shock). This scenario could unfold if a large country stops nuclear power production, or perhaps due to an innovation in the area of fuel efficiency, which has been simulated. In this scenario it has been assumed that an innovation in the area of nuclear fuel cladding occurs that allows traditional light water reactors to extract more energy (two thirds more) from a given amount of uranium. At present a limiting factor on the lifetime of the fuel is damage sustained to the fuel cladding as a result of the extreme environment in which it operates. If new materials are developed that can withstand high temperatures and radiation exposure, then more efficient use can be made of the uranium fuel without having to redesign existing reactors or make major changes to the fuel cycle [Grimes and Nuttall, 2010; Hallstadius *et al*, 2012]. Such an innovation is foreseeable in the horizon considered in this study, but as more research is needed it is not considered to take effect until after 2030.

In this high burn-up fuel scenario, demand would decrease, but uranium production would likely remain at the same level for a given time owing to inertia in the system. Figure 8 shows the ameliorating effect that an innovation in fuel efficiency could have on the uranium market.

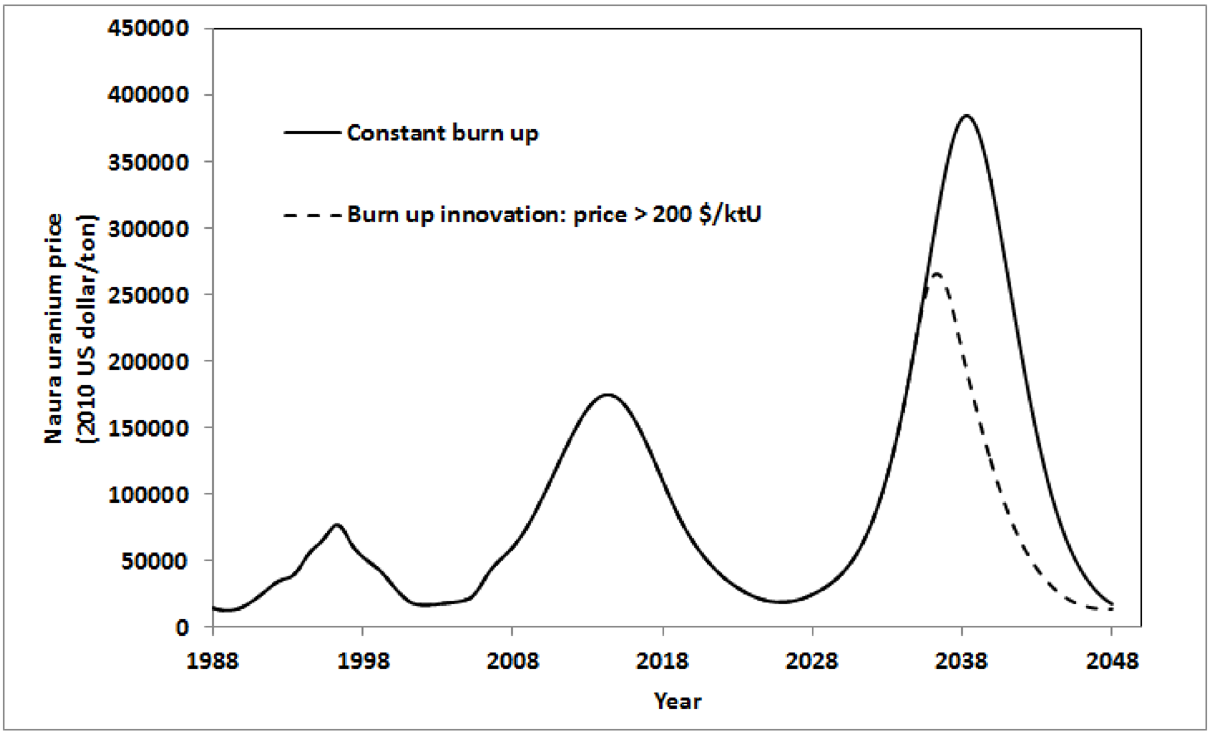

Figure 8: Effect of high burn-up fuel innovation on price. An explanation of the importance of such an innovation is provided in the text.

4. Conclusions

To study the dynamics of the uranium market, a system dynamics model of the nuclear fuel cycle has been created that runs from 1988 to 2048. Analysis using this model illustrates some of the key features of the market for this commodity, including the key role that time lags play in the formation of price volatility. Various demand reduction and substitution strategies and technologies are explored leading to the following potentially useful conclusions for the pertinent industry:

- Uranium resource scarcity is not likely to be an issue until the second half of the twenty first century at the earliest, even if high uranium demand projections are realised.
- The ending of the “Megatons to Megawatts” program, in which the USA agreed to buy down-blended uranium from former Soviet nuclear warheads for use in power production, without substitute sources lined up, could have a significant positive effect on uranium price.
- The time constant relating to traders’ expectations of future market prices has a strong influence on both the amplitude and frequency of price peaks. Price expectations formation should therefore become the focus of future research studies in this area.

5. Acknowledgements

This paper is substantially derived from an MPhil thesis submitted to Cambridge Judge Business School in June 2012. We would like to thank Dr Stephen F. Ashley, whose technical advice was crucial to completing the study. We would also like to thank the numerous experts who lent their time to assist in developing the system dynamics model.

One of us (Matthew Rooney) would like to acknowledge financial assistance from AREVA, who provided him with a scholarship to cover university fees and expenses.

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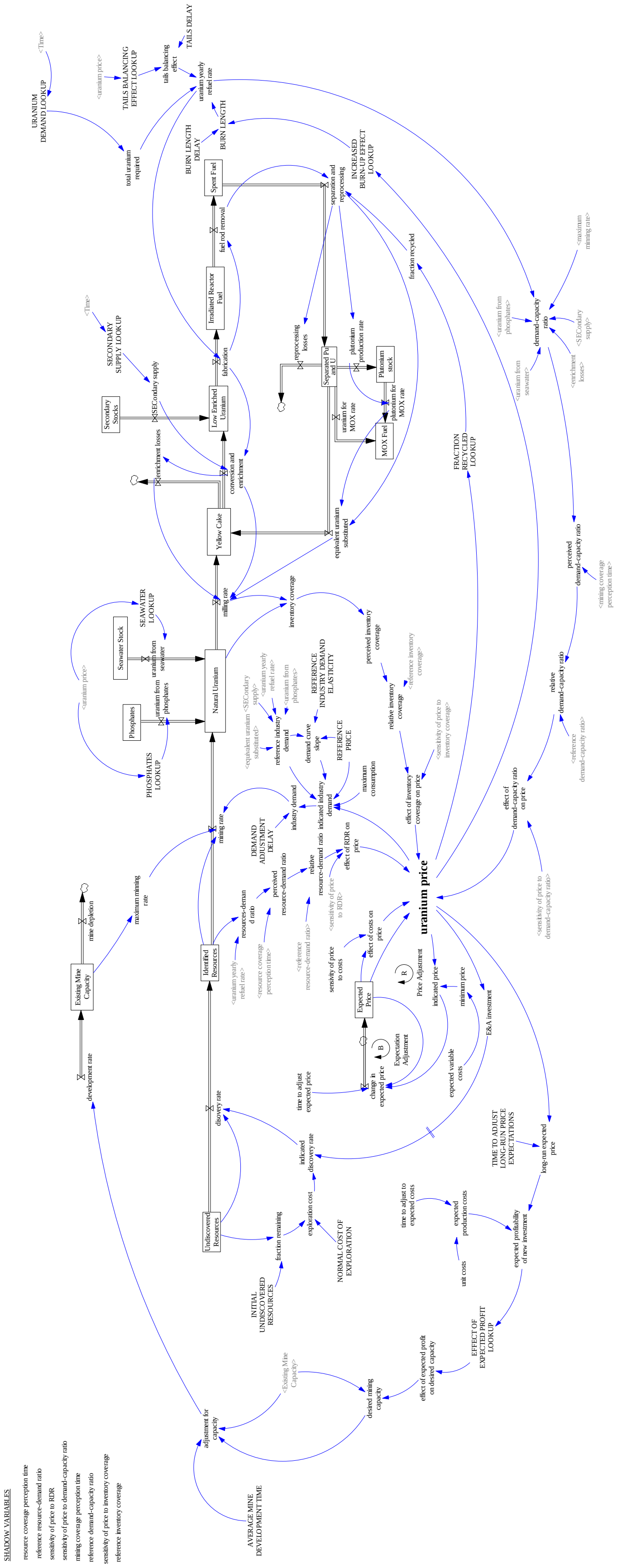
Appendix 1: Full system dynamics model, created using Vensim [Ventana Systems Inc., 2010]



Appendix 2: Experts consulted in the model development process

Arnold, N. (2012) Researcher at the University of Natural Resources and Life Sciences, Vienna. Telephone interview on 27th April 2012.

Ashley, S. (2012) Post-doctoral researcher in the Cambridge University Electricity Policy Research Group. Meeting on 3rd April 2012.

Emsley, E. (2012) Economist at the World Nuclear Association. Meeting on 2nd May 2012.

Tulsidas, H. (2012) Nuclear Technology Specialist at IAEA. Telephone interview on 27th April 2012.

Skelton, B. (2012) Semi-retired academic in chemical engineering at the University of Cambridge. Meeting on 11th April 2012.