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A dynamic model of the global uranium market and the nuclear fuel cycle

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ABSTRACT

In order to study the global uranium market, a dynamic model for the period 1990–2050 has been developed. It incorporates globally aggregated stocks and flows of uranium moving through the nuclear fuel cycle, as well as a price formation mechanism. 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. Specific demand reduction and substitution strategies and technologies are explored, and potential external shocks are simulated to investigate the effect on price and how the uranium mining industry responds. Sensitivity analysis of 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. Finally, our analysis leads us to believe that the existing uranium resource base will be sufficient to satisfy demand well into the second half of the 21st century.

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) and the OECD Nuclear Energy Agency (NEA) make a projection that installed nuclear capacity will increase, even in their low scenario projections that assume their most pessimistic outcome for new reactor build (OECD-NEA and IAEA, 2012; IAEA, 2012). 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 decline as a share of world supply.

The sustainability of uranium as a fuel source is therefore an important topic for study and it has come under scrutiny in recent years (MIT, 2010; Matthews and Driscoll, 2010; Dittmar, 2013; 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.

System dynamics is a well-established tool for modelling and analysis 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 of a system dynamics model of the uranium market and nuclear fuel cycle that runs from 1990 to 2050. The objective in building the model is not to predict the future with certainty, but to study the behaviour of the pertinent market, 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 analysis involving key model inputs.

The basic nuclear fuel cycle under consideration is shown in Fig. 1. For clarity the complicated structure of auxiliary variables has been removed (though the full model with equations is included in the Appendix). 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 years in a reactor the spent fuel is removed and stored for later disposal or reprocessing.

Once a power plant has been 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

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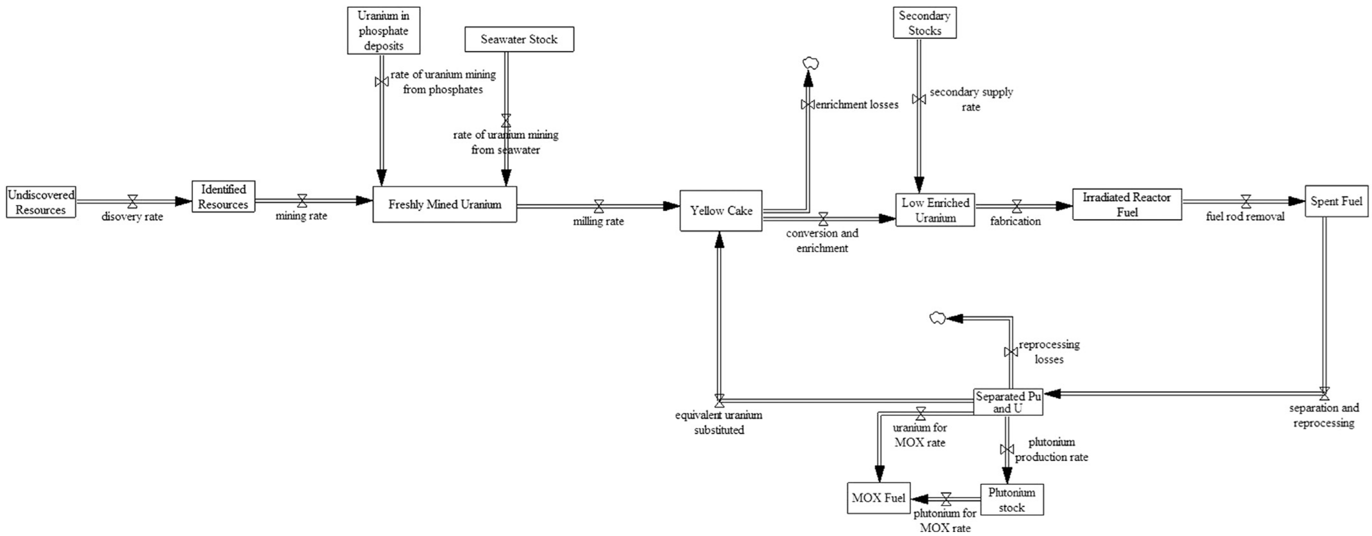

Fig. 1. Schematic diagram showing the flow of uranium through the nuclear fuel cycle (model created using Vensim software Ventana System Inc. (2010)).

majority). Furthermore, the industry has a strong willingness to pay higher prices in the event of constrained supplies. For this reason, the total amount of uranium on a global scale required is treated as an exogenous model parameter and high and low 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 focuses mostly on the uranium mining sector and simulates what fraction of uranium demand will be met through traditional mining, stockpile draw-down, unconventional supplies, and also reprocessed and recycled spent fuel.

Based on expert consultations with industry and academic experts[1] 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 represents a by-product of phosphates 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 expand slowly from its current low base 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 introduced 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 ($/tU) of natural uranium 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 $300 t/U for many years, and can be viewed as a proxy for all unconventional high cost sources of uranium that are not presently mined.

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 are 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[2] fission reactors and nuclear fusion. Given that the model runs until only 2050, along with the fact that it can take more 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.

Theoretical background and methodological approach

The system dynamics model draws on the structure of the generic commodities model outlined in *Business Dynamics* (Sterman, 2000) (which was in turn based on work by Meadows (1970)), 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

[1] The following experts were interviewed throughout 2012: Arnold, N. Researcher at the University of Natural Resources and Life Sciences, Vienna (telephone interview on 27th April 2012); Ashley, S. Post-doctoral researcher in the Cambridge University Electricity Policy Research Group (meeting on 3rd April 2012);Emsley, E. Economist at the World Nuclear Association (meeting on 2nd May 2012); Tulsidas, H. Nuclear Technology Specialist at IAEA (telephone interview on 27th April 2012); Skelton, B. Semi-retired academic in chemical engineering at the University of Cambridge (meeting on 11th April 2012).

[2] Reactors can be generally classified into four generations: Gen-I were prototype reactors built in the1950s; Gen II developed from these prototypes and were built from the 1960s to 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).