Resources Policy 53 (2017) 394–407

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

Long-term availability of global uranium resources

Antoine Monnet[a], Sophie Gabriel[a,*], Jacques Percebois[b]

[a] French Alternative Energies and Atomic Energy Commission, I-tésé, CEA/DAS, Université Paris Saclay, F-91191 Gif-sur-Yvette, France
[b] Université Montpellier 1 – UFR d'Economie – CREDEN (Art-Dev UMR CNRS 5281), Avenue Raymond Dugrand, CS 79606, 34960 Montpellier, France

ABSTRACT

Against a backdrop of decarbonisation in the energy sector and the increasing share of nuclear power in the global power mix, availability of uranium resources presents a major challenge. Since it will be some time before technologies of future nuclear reactors which remove the reliance on natural uranium are fully deployed, it is relevant to analyse the availability conditions for uranium in the 21st century.

The first two conditions - technical accessibility and economic value - are associated with production cost. We study these by modelling the ultimate uranium resources (including both identified and undiscovered resources) and their cost. This method is based on a regional breakdown of global uranium resources, current known deposits and an economic filter. It allows us to establish a long-term supply curve in which the quantities of technically accessible uranium resources are represented as a function of production cost.

The other uranium availability conditions considered are associated with market dynamics, which created by the relationship between supply and demand. These are modelled in the form of dynamic constraints in a partial equilibrium market model. This is a deterministic model in which the market players are represented by regions. It allows us to take account, for instance, of the short-term correlation between price and exploration expenditure. In the longer term, the constraints modelled include anticipation of demand from electric utilities (the consumers) and the increasing scarcity of the least costly ultimate resources.

Using a series of forward looking simulations, we demonstrate that the rate of growth in demand for uranium in the 21st century and its anticipation have a major impact on the increase in price in the long-term. Conversely, uncertainties related to the estimation of ultimate resources have a limited effect. Lastly, some variations in supply (uranium production shutdown in a particular region, for example) or demand (irregular increase) also have a significant impact on long-term price trends or cycles.

1. Introduction

Determining the supply of natural uranium is a high priority for the future of nuclear energy, in terms of competitiveness and sustainability. Current generation of light water reactors (LWRs) benefits from a significant competitive advantage over other centralised sources of electricity production in that their fuel represents a small percentage of their overall cost. In the future, if uranium resources become scarcer and their price rises sharply, this advantage may be lost, thus compromising the competitiveness of nuclear power over other centralised electricity production sources, or even compared with nuclear technologies having a lower consumption rate of natural uranium. The study of uranium availability conditions in the 21st century has been the subject of a 3-years research programme (Monnet, 2016) which is summarised in this article.

For the basis of this analysis, we first developed a model for estimating the "**ultimate resources**" of uranium (see Section 2). This model was used to quantify the technically accessible uranium resources on a regional and worldwide scale and to estimate their associated production costs. The result is represented by a **long-term cumulative supply curve** (LTCS).

In order to be able to develop a market model, we then identified the **dynamic constraints** impacting the long-term supply of uranium (see Section 3). These constraints have a direct impact on either exploration or production. Analysis of annual exploration activity and the associated discovery costs allowed us to introduce two key relationships which were subsequently used in the market model developed. Two original uses of the R/P (reserves-to-production) ratio are also introduced to model the constraints associated with anticipation of demand and security of supply.

The study of the balance between supply and demand over time has helped to develop a uranium market model by considering that the long-term dynamic is a succession of short-term (annual) equilibria (see Section 4). This involves a deterministic economic model, in

---

[*] Corresponding author.
E-mail address: sophie.gabriel@cea.fr (S. Gabriel).

http://dx.doi.org/10.1016/j.resourpol.2017.07.008
Received 14 March 2017; Received in revised form 31 May 2017; Accepted 27 July 2017

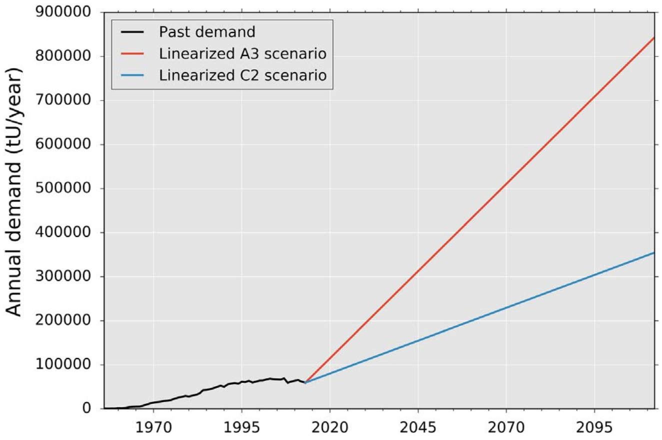

Fig. 1. Cumulative global uranium consumption scenarios (Baschwitz et al., 2009).

partial equilibrium given that it only takes account of the uranium market.

This is the market model that was ultimately used for the forward looking simulations based on exogenous demand scenarios (see Section 5).

Our analysis was not based on modelling demand scenarios as this involved too many underlying assumptions, hence we adopted a literature review based approach (IIASA et al., 1998). Two demand scenarios were subsequently selected: **scenario A3**, representing high global demand for nuclear power (5,400 GWe installed capacity in 2100) with a consequently high demand for natural uranium (810 ktU/year); and **scenario C2**, representing moderate demand (2,100 GWe in 2100 and 340 ktU/year). No scenarios representing low growth or a reduction in the world's nuclear fleet were considered based on their limited relevance to the study (the availability of uranium resources is not a constraint in either of these scenarios).

2. Modelling ultimate resources

Several bivariate and multivariate statistical models can be found in the literature to estimate the abundance and production costs associated with a non-ferrous metal such as uranium. The statistical models give an economic assessment at deposit level then provide a sum of all the deposit resources. One advantage of this approach is that models can be specific to each geological environment. Among the models reviewed in the literature, three have been applied to uranium. They were developed by Chavez-Martinez (1982), Harris (1977, 1984, 1988), Drew (1977) and Brinck, (1967, 1971), De Wolde et al. (1971) at the end of the 1970s, early 1980s. None of them were used to establish a complete long-term cumulative supply (LTCS) curve of world resources, however; they were essentially used to estimate potential reserves (undiscovered resources which could be produced at a lower cost than the market price at the time the studies were conducted) (in the case of Drew and Brinck) or to estimate the ultimate resources in different cost categories, but within a specific region of the world (in the case of Drew and Harris).

In addition to these models, a more advanced method, called *Quantitative Mineral Resource Assessments*, has been developed by the United States Geological Survey (USGS) and applies to all non-ferrous metals (Singer, 2007). One additional purpose of this method is to locate undiscovered resources: within a geological environment, subregions are delimited and data from the Geographic Information System (GIS), available in well-explored subregions, are analysed to find similarities with unexplored or less well known subregions.

This aspect of locating undiscovered resources is not included in our approach and our model has been inspired more by the work of Harris and Drew than the more recent studies by the USGS.

Our methodology allows for an estimation of ultimate uranium resources based on a lognormal distribution of the grade and tonnage of deposits, on the use of an economic filter and on cost functions which take account of economies of scale and the type of mining involved. By calibrating these distributions and cost functions differently, our model takes greater account of the data available, as well as the specific economic and geological characteristics of each region.

2.1. *Statistical approach based on geological environments*

2.1.1. *Crustal abundance model*

The geological abundance (q), or crustal abundance, of known and undiscovered resources in a given environment can be defined on the basis of the total quantity of metal present in the geological environment in question (q_0) and a probability density function of grade and tonnage $f(g,t)$ as follows:

$$q = q_0 \iint f(g,\, t)dgdt \tag{1}$$

q_0 is estimated from the mass of rock M in the geological environment and the mean grade of the crust *clarke* ($q0 = M \times clarke$). Note that q_0 does not include any consideration of economic value or recovery rate.

The numerical method used to determine the parameters of the statistical distribution of grade and tonnage $f(g,t)$ is inspired by the work of Drew. It uses a cost-grade-tonnage relationship as an economic filter (see below). The form of this relationship is inspired by the work of Drew and Harris, however its calibration is a separate procedure and the cost limit used in the filter is specific to our study. To model the costs for all deposits (known and undiscovered), our study proposes a method which is more representative of the industrial reality than that used by Drew and Harris. The numerical procedure used to calculate the cumulative resources at less than a given cost is also specific to this study.

It is worth mentioning here that our model is based on the assumption that uranium is the primary product, i.e. that it incurs all the investment and production costs associated with mineral extraction.

2.1.1.1. Lognormal distribution of grade and tonnage. It is common, although sometimes criticised, to assume that f follows a bivariate lognormal distribution (Harris, 1977) which results in the mathematical form of f described by Eq. (2), where grade g and tonnage t are assumed to be independent variables.

$$f(g,\, t) = \frac{exp\left(-\frac{(lng-\mu_x)^2}{2\sigma_x^2} - \frac{\left(lnt-\mu_y\right)^2}{2\sigma_y^2}\right)}{2\pi g t \sigma_x \sigma_y} \tag{2}$$

μ_x, σ_x^2 and μ_y, σ_y^2 are the means and variances of $x = ln(g)$ and $y = ln(t)$ respectively.

In a given geological environment, the statistics for g and t, taken from known deposits, can be used to determine the statistical distribution of grade and tonnage. Unfortunately, deposits are not sampled randomly. On the contrary, the richest deposits (high grade, high tonnage) tend to attract economic interest first.

2.1.1.2. Economic filter. To correct the sampling bias that affects known deposits (Harris, 1984), the idea is to model an economic filter. This filter is a function which truncates the probability density function of deposits and separates them into observable and non-observable deposits, according to whether they are above or below a given cost limit.

With this filter, the empirical data available corresponds mainly to observable deposits (known deposits may nevertheless be subeconomic due to the partially random exploration characteristic). Because of truncation, the grade and tonnage of observable deposits no longer