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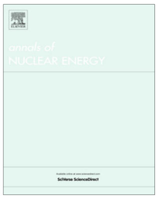

A critical assessment of global uranium resources, including uranium in phosphate rocks, and the possible impact of uranium shortages on nuclear power fleets

Sophie Gabriel *, Anne Baschwitz, Gilles Mathonnière, Tommy Eleouet, Florian Fizaine

CEA, DEN/DANS/I-tésé, F-91191 Gif-sur-Yvette, France

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ABSTRACT

Future energy demand scenarios elaborated by international organisations tend to be ambitious in terms of the installed nuclear power capacity, particularly when trying to absorb the effects of a growing world population, to account for GDPs and to curb greenhouse gas emissions.

Current light water reactors use thermal neutrons and burn uranium (a natural, finite resource), whereas some future Generation IV reactors using fast neutrons (starting with an initial fissile load) will be capable of recycling their own plutonium and already-extracted depleted uranium (self-sufficient or breeder fast reactors).

The availability of uranium therefore has a direct impact on the capacity of the reactors that we can build. It is therefore important to have an accurate estimate of the available uranium resources in order to plan for the world's future nuclear reactor fleet.

This paper discusses the correspondence between the resources (uranium and plutonium) and the nuclear power demand as estimated by various international organisations. Furthermore, the estimate of how much uranium can be recovered from phosphate rocks is questioned and the impact of our downscaled estimate on the deployment of a nuclear fleet is assessed accordingly.

1. Introduction

The production of carbon-free energy is a key issue in the fight against global warming. Future energy demand scenarios elaborated by international organisations tend to be ambitious in terms of the installed nuclear power capacity, particularly when trying to absorb the effects of a growing world population, to account for GDPs and to curb greenhouse gas emissions.

Current light water reactors use thermal neutrons and burn uranium (a natural, finite resource), whereas some future Generation IV reactors using fast neutrons (starting with an initial fissile load) will be capable of recycling their own plutonium and already-extracted depleted uranium (self-sufficient or breeder fast reactors).

The availability of uranium therefore has a direct impact on the capacity of the reactors that we can build. It is therefore important to have an accurate estimate of the available uranium resources in order to plan for the world's future nuclear reactor fleet.

This paper aims at examining the differences between the resources (uranium and plutonium) and the nuclear power demand as estimated by various international organisations.

Uranium is currently produced from conventional sources. The estimated quantities of uranium evolve over time in relation to their rate of extraction and the discovery of new deposits. Contrary to conventional resources, unconventional resources – because they are hardly used – also exist. These resources are more uncertain both in terms of their quantities and the feasibility of recovering them.

After having reviewed current knowledge on conventional uranium resources, the first part of this paper focuses on unconventional resources such as those potentially recovered from phosphate rocks.

In line with these considerations and taking into account different assumptions on the limited quantities of available uranium, this paper examines the correspondence between the estimated resources and the forecast energy scenarios. The second part of this paper first examines the current type of light water reactors which burn uranium, before examining a mixed fleet with both light water reactors and fast reactors which use plutonium.

2. Primary supply of uranium

Since the mid-sixties, in cooperation of the Member Countries and States, the OECD's Nuclear Energy Agency (OECD/NEA) and the International Atomic Energy Agency (IAEA), have regularly updated their report which summarises the current status of uranium exploration, resources and production, together with

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* Corresponding author. Tel.: +33 169082743; fax: +33 169083566.
E-mail address: sophie.gabriel@cea.fr (S. Gabriel).

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the nuclear power plant requirements. The latest version of this report, generally called the “*Red Book*”, is titled “*Uranium 2011: Resources, Production and Demand*” (OECD/NEA IAEA, 2012). This is the only source of information on the worldwide uranium ‘resources’ which is published every 2 years. In addition, official data are available in some countries (United States, Canada, etc.), while some mining groups publish data as part of their financial communication, the quality and content of which are standardised by the Stock Exchange authorities.

Note: as the studies discussed below date prior to July 2012 (publication date of the last Red Book), the figures from the 2010 version (OECD/NEA IAEA, 2010) have been maintained.

Resource assessments in this Red Book are divided into distinct categories that stand for different degrees of certainty concerning the indicated amounts. The resources are subdivided into ranges on a production cost basis, i.e. the cost of recovered uranium at the ore processing plant.

So-called ‘*conventional resources*’ are those that allow uranium to be recovered as a primary product, a co-product or a major by-product (e.g. in copper or gold mines). ‘*Unconventional resources*’ are very low-grade resources and those from which uranium is only recoverable as a minor by-product. Uranium is therefore a secondary product and its recovery is not subjected to most of extraction costs. The boundary between conventional and unconventional resources is not clear-cut, and rather stands as a kind of transition zone.

2.1. Conventional resources

Conventional resources consist of identified resources and undiscovered resources (see Table 1).

Identified resources consist of ‘Reasonably Assured Resources’ (RARs) and ‘Inferred Resources’ recoverable at costs lower than or equal to USD 260/kg U.

Undiscovered resources consist of ‘Prognosticated Resources’ and ‘Speculative Resources’.

The information on resources cited is the best available today, but it can change as uranium resource figures are dynamic and depend on the market prices. On the one hand, high prices give rise to optimistic forecasts, whereas low prices result in more pessimistic assessments. Nonetheless, market prices determine prospecting expenditure as well as cutoff grades and other parameters used in resource calculations.

We have to take into account the limitations of current resources estimates following 20 years of low prices prior to 2003 that provided little incentive for exploration activity. Despite exploration efforts spanning 50 years, a significant area of the earth has not been explored using modern techniques. With increased exploration activity, new deposit models and exploration techniques, there is a potential to increase known uranium resources.

Given the increased prices for uranium that can reasonably be expected if nuclear energy does expand, significant uranium discoveries can be expected to occur, just as they have in past periods when rapid nuclear capacity growth expectations triggered price increases and, in turn, uranium exploration that led to discoveries.

Otherwise, reporting of undiscovered resources is incomplete. Some of the countries that do not report undiscovered resources, such as Australia, Gabon and Namibia, are considered to have significant resource potential in as yet sparsely explored areas.

Therefore, uranium resource figures are a “snapshot” of the available information on resources of economic interest; they are not an inventory of the total amount of recoverable uranium in the earth’s crust. When the market conditions are favorable and boost prospecting activities, additional discoveries may be expected, just as in past periods of heightened prospecting activity.

2.2. Unconventional resources

Uranium recovery from unconventional resources has to take into account economic criteria and trends in the primary uranium market. Otherwise, it must be part of large-scale operations in which economies of scale partly compensate for the ore’s low grade.

There are multiple unconventional uranium resources but this paper takes into account the most abundant resources, i.e. seawater and phosphate rock deposits.

2.2.1. Seawater

Uranium is found in seawater in very small concentrations (3.3 μg/l), which nonetheless represents almost 4.5 billion tonnes of uranium considering the volume of the oceans and seas. The very low concentration of uranium in seawater requires processing enormous volumes of water to recover significant quantities of uranium. Only processes using strong natural currents without pumping would be economically viable.

A number of industrial extraction models have been developed since the fifties. The extraction technology has been validated on a laboratory scale but there is currently no industrial or semi-industrial application is use. Most of the teams have stopped their research, though Japan hopes to reach a production cost of about 300 $/kg U (Masao, 2009). This figure is based on a set of very optimistic assumptions and is probably unrealistic. New efforts are underway in the United States to assess recovery costs using improved new systems http://www.eurekalert.org/pub_releases/2012-08/acs-aid072612.php. Even if it is technically possible to extract uranium from seawater, the cost estimates are such that an industrial application is hardly possible except in the case of a major technical breakthrough.

2.2.2. Phosphate rocks

Phosphate rocks are a source of phosphorus – a vital element for plants. Phosphorus is one of the main raw materials used to make fertilizers and is also used in food supplements, drinks, and others industrial products.

Phosphate deposits may be classified into two categories: igneous phosphate rocks (13%) and sedimentary phosphate rocks (87%) (Van Kauwenbergh, 1997). The presence of uranium in phosphate rocks can be explained on an atomic scale, by the substitution of a calcium atom by a uranium atom in the crystal lattice of the phosphates (apatite) (Kratz and Schnug, 2006; Cuney, 2008; Samb, 2007). Uranium can also be adsorbed on apatite crystal surfaces.

An assessment of the available uranium reserves in phosphate deposits first requires an accurate estimate of the phosphate

Table 1
World conventional resources in uranium (MtU) (source: Red Book 2010 (OECD/NEA IAEA, 2010).

	Conventional resources (MtU)			
Recoverable at costs	Identified resources		Undiscovered resources	
USD/kg U (USD/lbU_3O_8)	Reasonably assured	Inferred	Prognosticated	Speculative
<40 (<15)	0.6	0.2	1.7	
40–80 (15–30)	1.9	1.0		
80–130 (30–50)	1.0	0.7	1.1	
130–260 (50–100)	0.5	0.4	0.1	
Sub-total	4.0	2.3	2.9	7.5
Total	6.3		10.4	

Note: the Red Book published in 2012 cites 7.1 Mt of identified uranium resources (OECD/NEA IAEA, 2012).

reserves and then an estimate of the uranium content in these deposits.

2.2.2.1. Uncertainty of phosphate reserves. Various figures are available on the phosphate reserves, e.g. USGS (2011), IFDC (2011), and an old American report (De Voto and Steven, 1979).

The USGS in 2011 estimates the world phosphate reserves to be equivalent to 65 Gt. This estimation has radically evolved from the 15 Gt estimated in 2009. This change probably results from the merging of two categories: phosphate reserves and base reserves. Base reserves currently include economic and marginal economic reserves, together with reserves that have a sub-economical interest which initially cost less than $100 per tonne. With the phosphate price increase, from $44 to $102 (constant $2000) per tonne between 2000 and 2010, the phosphate base reserves category can be considered as the part of the global reserve which is economically extracted or produced at the time of determination.

Gilbert (2009) explains that the estimate of 65 Gt of phosphate reserves includes both 15 Gt of immediately recoverable phosphates at the market price and 50 Gt of phosphate resources with more impurities and more constraints to take into account like offshore deposits. He also specifies that the USGS got its data from foreign governments without independent audits on reported reserves. Therefore, the uncertainties of phosphate reserves in the world imply the uncertainty of the uranium reserves recovered from phosphates.

The 65 Gt of phosphate reserves are essentially located in Morocco (77%), China (6%), Algeria (3%) and Syria (3%). However, the production of phosphate (176 Mt in 2010) differs: China ranks as the first producer (37%) followed by Morocco (15%) and the US (15%). The US phosphate production has been declining since the beginning of the century, whereas China has considerably increased its highly cost-effective production. The phosphate production in Morocca has not really changed over the past 20 years.

The IFDC estimate of the phosphate reserves is 60 Gt, which is very similar to the USGS assessment. In fact, most of the data used by the USGS was provided by the IFDC, especially for the Moroccan reserves. Again, according to Gilbert (2009), the IFDC is an association of fertilizer producers and some experts have doubts on the accuracy of the figures published by the IFDC, arguing that they have vested commercial interests.

The De Voto and Steven report (1979) assumed 223 Gt of recoverable phosphate rocks, but this assessment was only for the US. It rose to 293 Gt when it was extended to the 'Free World'. The global distribution of phosphate reserves in this report differs from the current USGS assessment. According to De Voto and Steven, the US totalled 76% of the global recoverable phosphates, while the USGS estimation in 2011 indicates that the US represents only 2.1% of the total phosphate reserves. Obviously, the global figure of 65 Gt quoted by the USGS is also radically different from the 293 Gt cited by De Voto and Steven, so this figure is surely outdated and can be excluded.

2.2.2.2. Uncertainty of the available amount of uranium. The uranium content in phosphate deposits varies both within a deposit and between different deposits. Several studies have reported an average concentration of uranium close to 100 ppm (parts per million) in phosphate rocks (Kennedy, 1967; OECD/NEA IAEA, 2010; Kratz and Schnug, 2006; Van Kauwenbergh, 1997; Barthel, 2005). However, the actual concentration can range between 23 and 220 ppm. Igneous phosphates seemingly contain, on average, less uranium than sedimentary phosphates – 59 ppm instead of 96 ppm – but the distribution of concentration is more heterogeneous and can reach 200 ppm or more, as has been found in some Brazilian deposits.

The Red Book mentions several estimates for uranium reserves in phosphate rocks to underline the uncertainties of all these estimates:

- 22 MtU based on the De Voto and Steven report (1979).
- 9 MtU in the IAEA report 2001 (IAEA, 2001).
- 7.3–7.6 MtU reported in 1965–1993 Red Books.

The 22 MtU from De Voto and Steven is often given as the upper limit for the uranium contained in the phosphate reserves. However, this estimation is the most questionable because it is based on a recoverable phosphate rock estimation of 223 Gt, an outdated figure.

Furthermore, the IAEA coordinates a database named UDEPO (2011) which references the majority of the uranium deposits with a tonnage superior to 500 tonnes of uranium. In April 2011, UDEPO announced 7.8 MtU for the uranium content in phosphate rocks deposits. Since June 2011, this estimation has shifted to 12.9 MtU without any explanation for this change.

Keeping in mind the uncertainties on the phosphate rock reserves and their uranium concentration, the uranium that can be recovered from phosphate reserves is assessed in this paper.

Assuming the global phosphate rock reserves to be 65 Gt (USGS, 2011) and based on the assumption of an average uranium concentration of 100 ppm in phosphate rocks (Kennedy, 1967; IAEA, 2010; Kratz and Schnug, 2006; Van Kauwenbergh, 1997; Barthel, 2005), 6.5 MtU is contained in phosphate rocks. This is very close to the last Red Book figures at 7.3–7.6 MtU but different from the 9 MtU specified in the 2001 IAEA assessment.

Nonetheless, this figure does not take into account inevitable losses due to the imperfection of many processes. Uranium can only be recovered from phosphate rocks by using phosphoric acid, which is a by-product of the wet phosphoric acid process and the first step to produce fertilizers. When phosphate rocks are dissolved with sulphuric acid, it generates both phosphoric acid and phosphogypsum. The majority of uranium passes into the phosphoric acid (93%) while only a minor proportion remains in the phosphogypsum (Guida and Royster, 2008). In addition, only 72% of phosphate rocks are used to produce phosphoric acid (Van Kauwenbergh, 2010; Birky et al., 2009). Finally, the rate of uranium recovery from the phosphoric acid can reach 90% with the DEHPA-TOPO process (McCarn, 1998; Walters et al., 2008). Considering all these losses, 3.9 MtU is expected to be recovered from the 6.5 MtU contained in the phosphate reserves. In fact, this figure could fall to 3.4 MtU when excluding igneous phosphates rocks (13% of the global phosphate rock reserves) which are known to contain a lower uranium concentration and could be unprofitable.

2.2.2.3. Uranium as a by-product of phosphates. The production of a by-product depends on the production of the main product, which is why uranium recovery from phosphates is limited by the phosphate production.

Assuming an annual phosphate production of 176 Mt, with a concentration of 100 ppm of uranium in phosphate deposits and assuming that 72% of the phosphate production is devoted to phosphoric acid with a global rate of recovery of 84%,[1] then the maximum uranium production from the phosphates is 10.6 kt U/y.

This result is very close to the 11 kt U/y estimated by the IAEA (2001). Nonetheless, this result is marred by imprecision, in particular the lack of distinction between igneous and sedimentary phosphates or the possible variation in the average uranium

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[1] The global recovery rate includes 7% of uranium lost in phosphogypsum and 10% misplaced during the recovery of uranium from phosphoric acid with the DEHPA-TOPO process.

concentration in phosphate rocks. The previous assumptions, with the exception of an average uranium concentration of 200 ppm, would lead to a production of 21 kt U/y. In the case of a less optimistic assumption, with an average concentration of 60 ppm of uranium and excluding igneous phosphate rocks (assumed as 13% of the phosphate rock production), the uranium production derived from phosphates would only reach 5.5 kt U/y.

According to various different studies (Kennedy, 1967; De Voto and Steven, 1979; McCarn, 1998; IAEA, 1989, 2007; Jackovics, 2007; World Energy Council, 2007; Walters et al., 2008; Knapp et al., 2010), the cost of recovering uranium as a by-product from phosphates would range between $60 and $200/kg U which means it is already economically profitable today. Nonetheless, no one in the industry has made a move in this direction. This is most probably because of concerns related to the specific regulations governing the production of uranium.

2.2.2.4. Uranium as a primary product of phosphates. Despite a significant supply of 10.6 kt U/y, phosphates will not provide more than 16% of the current world demand (63.9 kt U/y OECD/NEA IAEA, 2012) and probably much less in the future with the growing uranium demand. To meet the current uranium demand, production needs to be increased sixfold (1 Gt/y compared with 176 Mt/y currently). At this rate, the phosphate rock reserves declared by the USGS will be depleted after 64 years.

To get around this limited production and meet the world demand at the same time, uranium should be recovered from phosphate rocks as a primary product. In this case, uranium should bear all the costs: extraction, phosphoric acid production and uranium recovery.

The expected cost of production – according to the different hypotheses – should range between $1300 and $6300/kg U, which is largely prohibitive and therefore hardly feasible (Gabriel et al., forthcoming).

3. Developing nuclear power with limited uranium resources

In the energy sector, the demand must be estimated several years or even several decades in advance. The construction of power plants cannot be improvised because of the duration of the construction works and the time needed to obtain the various authorisations and licenses. This is particularly true when it comes to planning the production of nuclear power.

Energy scenarios are only uncertain estimates of what the future electricity market may become; they are an estimate of what may happen based on current knowledge of how the world is evolving, on demographics, the GDP, the energy intensity, and political decisions made by the different countries. These scenarios can be used to analyse the construction of different types of reactor technologies and to determine the related requirements in resources (uranium and plutonium).

This paper aims at assessing the impact of limited quantities of available uranium on these scenarios. Case studies are used to illustrate the uranium requirements according to the different global nuclear power growth scenarios and to stress the fact that more resource-saving reactor technologies must be deployed to ensure the sustainable development of the industry.

3.1. Energy scenarios

In our past forecasting studies on the development of nuclear power (Baschwitz et al., 2009b), we chose to work with the IIASA (1998) scenarios which, at the time, were the only scenarios providing an energy mix for the 21st century. More recent scenarios IIASA (2007), WNA (2010), and IAEA (2010) predict much higher installed nuclear power estimates, yet we believe their feasibility remains uncertain.

In 2012, the World Energy Council (WEC) published a report entitled “World Energy Perspective: Nuclear Energy One Year After Fukushima” (World Energy Council). This strictly qualitative report tends to suggest that the general trends described by the scenarios published before the Fukushima nuclear accident are still valid, and that the anticipated growth of world nuclear generating capacity will probably materialise.

After all, we have chosen to conserve the IIASA scenarios from 1998 (Global energy perspectives IIASA/WEC, 1998) for this study (see Fig. 1).

The *A2 Scenario* is a strong global growth scenario of around 2.7% per year, with the preferred short-term use of oil and gas resources. Nuclear energy represents 4% of world energy demand in 2050 and 21% in 2100.

The *A3 Scenario* is also a strong global growth scenario with a more gradual introduction of nuclear energy than in scenario A2; nuclear energy represents around 11% of world energy demand in 2050 and 22% in 2100.

The *B Scenario* is a “business as usual” world growth scenario during the 21st century (around 2% per year).

The *C2 Scenario* corresponds to a strong intention to protect the environment against global warming. Nuclear energy represents around 12% of world demand for primary energy in 2050; this is close to twice as much as it represents today.

The IIASA scenarios consider a strong increase in the world demand in primary energy. Even if the share of nuclear power is less than 20% of the total, it supposes a quite significant increase in the installed nuclear power capacity.

3.2. Reactor technologies

This study takes into consideration three different reactor technologies:

- Pressurised water reactors (PWRs). These Generation II reactors are representative of the reactors currently operating throughout the world today.
- European pressurised (or Evolutionary Power) Reactors (EPRs). These Generation III reactors are representative of what is currently being built or scheduled for construction throughout the world.
- Fast reactors (FRs). These Generation IV reactors use plutonium as fissile material.

It is considered that there is no recycling of fissile material in PWRs and EPRs.

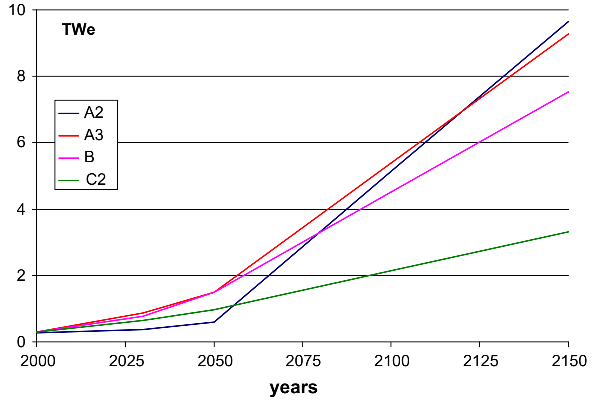

Fig. 1. IIASA scenarios requested nuclear power.

Table 2
Characteristics of the different reactor technologies.

Characteristics of each technology	Unit	PWR	EPR	FR
Lifetime	Years	40	60	60
Mass of reactor core	Tonnes	81	126	51
Mass of Pu in the core	Tonnes	–	–	12
Kd	%	77	90	90
Self-consumption	%	1	1	1
Efficiency	%	33	37	40
Gross installed capacity	GWe	1.01	1.61	1.45
Burn-up	GWd/t	45	60	123
Uranium enrichment	%	3.7	5	–
Breeding ratio	%	–	–	0
Natural uranium requirement	t/TWh	22.3	19.4	–

The technical characteristics of these reactors are given in Table 2.

3.3. Secondary resources

As opposed to primary resources, conventional or unconventional, secondary resources include the following categories:

- Inventories of natural and enriched uranium, of civilian and military origin.
- Uranium and plutonium obtained by spent reactor fuel reprocessing–recycling.
- Plutonium obtained from weapons grade surpluses.
- Depleted uranium that could be re-enriched.

The available secondary resources (excluding plutonium and uranium from reprocessing) are negligible compared to the future uranium consumption. They can actually have an influence on the market short-term U, but much less in the long term.

Concerning the recycling of spent fuel in LWR, the re-enrichment uranium can save on average 13% of natural uranium and the mono-recycling of plutonium in MOX fuel can save 12% (Greneche, 2010). However, the recycling of spent fuel is currently low and therefore can only have a reduced importance on the demand for uranium (Baschwitz et al., 2009a).

3.4. Limits of available uranium reserves

Past forecasting studies (Baschwitz et al., 2009a, 2009b) were performed on the basis of the fact, thanks to seawater, there was no limit on the quantity of available uranium. The only consequence of consuming this uranium was the increased production cost. As mentioned earlier in this paper (Section 2.2), it turns out that the unconventional uranium resources recovered from phosphate rocks are not as significant as first estimated, and that the recovery costs could prove to be very high.

This paper therefore discusses four different limits of available uranium resources:

- 6 Mt, which represents the quantity of identified conventional uranium resources.
- 20 Mt, which comprises 16 Mt of both identified and undiscovered conventional uranium resources, together with 4 Mt from phosphate rocks.
- 38 Mt, which comprises 16 Mt of both identified and undiscovered conventional uranium resources, together with 22 Mt from phosphate rocks (former optimistic estimate).
- 90 Mt, which takes into account the hope that mining exploration will find substantial new resources; this figure is based on a very optimistic view rather than an evaluation.

Actually, it is not possible to say how much uranium might be available for mining in the coming years. Given the increased prices for uranium that can reasonably be expected if nuclear energy does indeed expand at the rate examined in the growth scenarios considered in this paper, significant uranium discoveries can be expected to occur. So the four limits of available uranium resources can also be used to make a sensitivity analysis.

The quantity of uranium consumed during the lifetime of the reactor is called ‘engaged uranium’. An EPR is only built if there is some foresight on the availability of uranium resources. When the consumed and engaged uranium exceeds one of the above-mentioned limits, it will be impossible to build a new reactor requiring uranium, i.e. an EPR in our case. The only reactors that can be built once this limit has been reached are fast reactors that operate with plutonium. Considering that plutonium has to be produced and is not available in unlimited quantities, it will become possible 1 day that we cannot build enough reactors and thus no longer match supply to demand.

3.5. Exclusive deployment of EPRs

Our first calculations are based on the assumption that only EPRs can be built and that fast reactors will never become available. When the consumed and engaged uranium exceeds one of the above-mentioned limits, it will be impossible to build a new reactor. This assumption underlines the importance of Generation IV reactors for the future of nuclear power.

Fig. 2 illustrates the demand and production of nuclear power (in TWhe) for the A3 and C2 scenarios.

When no other reactor can be built for lack of uranium, the installed power starts to drop and it no longer meets demand since

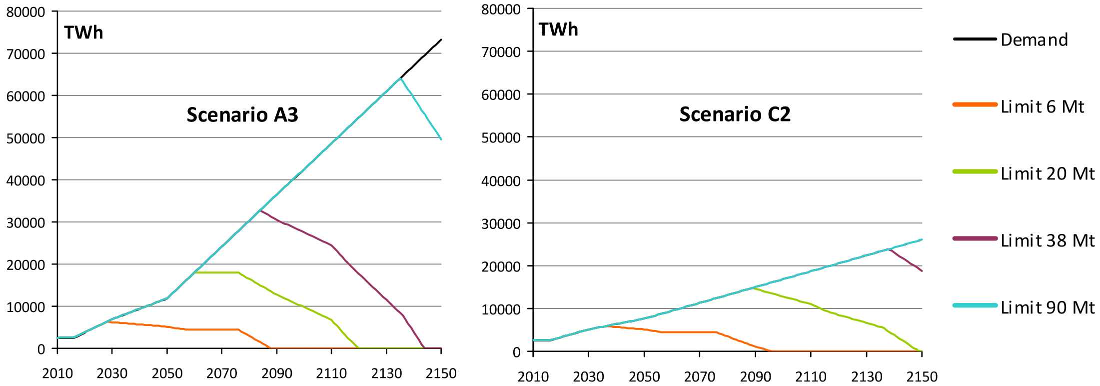

Fig. 2. Light water reactors only – demand and power production according to the natural uranium limit (TWhe).

Table 3
Scenarios and expected date of uranium shortage.

Scenario	A2	A3	B	C2
6 Mt limit	2051	2028	2030	2036
20 Mt limit	2069	2061	2063	2089
38 Mt limit	2090	2084	2092	2139
When the limit drops from 38 Mt to 20 Mt, the shortage occurs	20 years earlier	20 years earlier	30 years earlier	50 years earlier

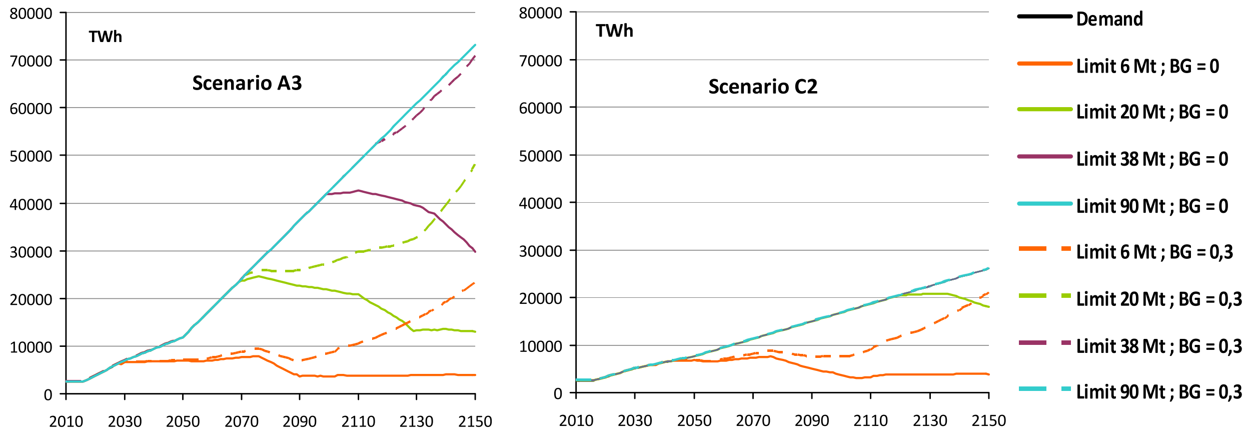

Fig. 3. Light water reactors and fast reactors – demand and power production according to the natural uranium limit (TWhe).

the reactors at the end of their lifetime cannot be replaced. Therefore, there is no more nuclear power production after 60 years.

The very ambitious A3 scenario shows that EPRs do not meet the entire nuclear power demand even with a uranium limit of 90 Mt. With only 6 Mt available, the problem of lacking resources arises in less than 20 years.

The C2 scenario represents the slowest growth of nuclear power with less pressure on the uranium resources. Nonetheless, only the uranium limit of 90 Mt will meet the nuclear power demand up to 2150.

Table 3 shows the dates at which the 6, 20 and 38 Mt will be consumed and engaged for the four chosen scenarios, i.e. the dates from which we will no longer be able to build EPRs and from which fast reactors will become necessary.

With 20 Mt, the uranium shortage will arise in the early 2060s for the three scenarios with the highest demand (A2, A3 and B), i.e. between 20 and 30 years earlier than with a 38 Mt limit. For the C2 scenario, the uranium shortage arises at the end of the century with 20 Mt, and 50 years later with 38 Mt.

These results stress the need to develop fast reactors in order to ensure the sustainable future of nuclear power.

3.6. Possible deployment of FRs from 2040

From 2040, we assume in our calculations that building fast reactors (self-sufficient reactors or breeder reactors with a breeding gain BG of 0.3 if necessary) will be given a top priority. We suppose that all the spent fuel can be reprocessed and that the reprocessing capacities are adapted to needs. There is no geopolitical consideration; we take the world as a whole unit which of course is a hypothetical case.

However, if there is an insufficient stock of available plutonium but still a sufficient supply of uranium, EPRs will be built. If both uranium and plutonium are lacking, no reactors will be built and it will be impossible to meet the demand.

Fig. 3 shows the possible nuclear power production for the A3 and C2 scenarios based on the availability of plutonium and the uranium limit taken into consideration (PWR and FR production).

For the C2 scenario with limited nuclear power growth, only the very restrictive limit of 6 Mt curbs the deployment of nuclear energy. Fast reactors with a breeding gain are necessary when the uranium limit is 20 Mt.

Considering the availability of plutonium and the limit in uranium, it is not possible to build as many EPRs and FRs as intended in the other scenarios.

It can be seen that a stable installed nuclear power capacity is reached with fast reactors when the latter are self-sufficient. Globally, 1 million tonnes of natural uranium used in PWRs would make it possible to produce enough plutonium to generate 85 GWe using fast reactors. The quantity of plutonium is not only distributed in the fast reactor cores, but also in the fuel cycle facilities.

Breeder reactors would make it possible to increase the installed nuclear power, though with certain uranium limits, we still remain below the estimated power requirements.

Table 4 indicates for each scenario at what time there will be no more uranium and not enough plutonium to satisfy the demand in nuclear power generation. Comparing to Table 3 we can see that fast reactors have little influence on this date. But of course the nuclear installed capacity is much bigger when fast reactors are available even if we do not satisfy totally the power requirements.

Fig. 4 indicates the reprocessing capacities that should be installed for the deployment of the fast reactor fleet, when fast reactors are self breeders. Their limited availability would, of course, restrain the deployment of the fast reactors.

Table 4
Date on which nuclear power requirements are no more satisfied.

Scenario	Breeding gain	A2	A3	B	C2
6 Mt limit	0	2054	2029	2031	2042
	0.3	2054	2029	2031	2042
20 Mt limit	0	2072	2070	2077	2120
	0.3	2074	2072	2080	–
38 Mt limit	0	2108	2100	2112	–
	0.3	2116	2117	–	–

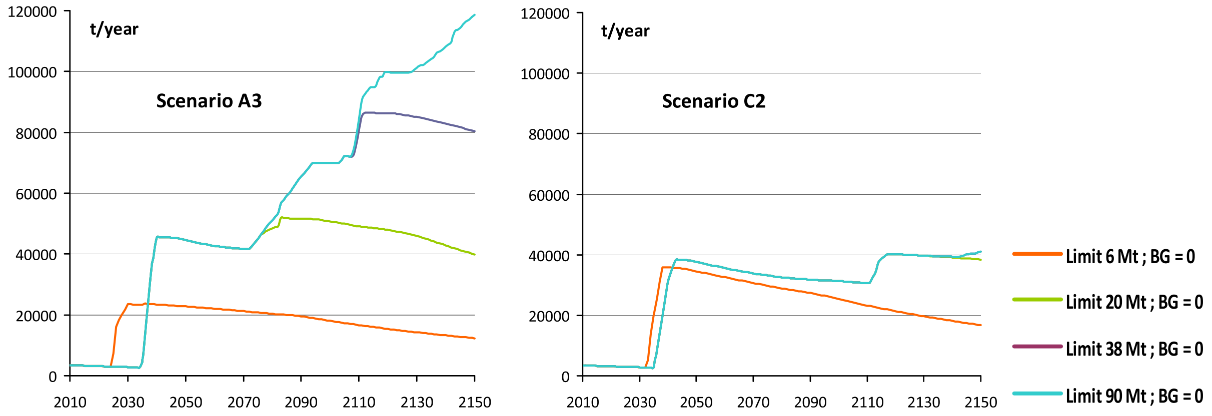

Fig. 4. Required reprocessing capacities.

4. Conclusion

Knowledge of the uranium resources is a prerequisite to studying nuclear power deployment scenarios. These resources are nevertheless ascertained with more or less uncertainty in terms of costs and quantities. Their estimates evolve as mining exploration progresses or as the economic conditions change.

The largely quoted estimate of 22 Mt of uranium recovered for phosphate rocks can be seriously downscaled. Based on our current knowledge of phosphate resources, 4 Mt of recoverable uranium already seems to be an upper bound value.

Given the various categories of resources and the uncertainties on each of them, it is wiser to take into account several different estimates of the available uranium quantities when studying global scenarios of the nuclear power demand since they reflect a more or less optimistic view of our future resources.

Considering light water reactors exclusively, 6 Mt and 20 Mt of uranium are required for the least ambitious C2 scenario up to 2036 and 2089 respectively when it will no longer be possible to build EPRs. However, it is possible to reach the end of the century with 38 Mt.

For the three other scenarios with higher demand, 38 Mt would allow for the construction of PWRs up to the end of the century, whereas construction would come to an end 20 or 30 years earlier with only 20 Mt.

The deployment of fast reactors and the recycling of materials therefore prove to be necessary, which is all the more true for scenarios with high growth. Their deployment is nonetheless restricted by the availability of plutonium and they do not meet the energy demand in all the scenarios. Self-sufficient reactors would make it possible it generate a stable installed power capacity equivalent to about 85 GWe per million tonnes of available uranium. Breeder reactors would significantly improve the situation since they would enable to nuclear fleet to continue its development. In any case, fast reactors make it possible to at least double the nuclear power production by 2150.

The large-scale deployment of nuclear reactors on an international level will require more uranium in the more or less long term. Recovering uranium from seawater would ensure a practically infinite resource of nuclear fuel, but its technical and economic feasibility have yet to be confirmed. The recovery of uranium from phosphate rocks will only ensure a limited resource. Mining exploration is therefore essential in the hope of discovering new sources of uranium.

It is also essential to examine how we can optimise the use of uranium. This raises the question of deploying fast reactors. To overcome the problem of plutonium availability, their first loads can use enriched uranium. So the deployment of a fast reactor fleet could be fast-tracked but at the expense of PWRs whose uranium resources would become even scarcer. Consequently, the growth and composition of the nuclear fleet would be modified (paper to be published).

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