[EHNUR WP 6]

NUCLEAR FUEL AND AVAILABILITY

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EXECUTIVE SUMMARY

To fight climate change and meet future energy demands on a global basis, new investments in nuclear energy are proposed by several institutions which expect a constant growth of nuclear energy share, at least in the developing economies in Asia over the next two decades.

One of the main aspects for every energy generation technology is the primary energy supply. In case of nuclear energy, uranium has been the fuel of choice in the past and likely will remain so for the upcoming new reactors. Thus the availability of uranium is a relevant aspect for the future development of nuclear energy. In this report an analysis of the current market situation of uranium has been made. Uranium resources, frame conditions for uranium production and a secured supply have been evaluated. Here, the uranium recovery by mining (primary resources) has been placed in the foreground but also alternative ways of supply were examined. This relates to the reprocessing of spent fuel, uranium stocks and the contribution by depletion of nuclear weapons uranium – so called secondary resources – as well as the extraction of uranium from phosphate ores or from seawater - called unconventional resources. The possible supply of thorium is also briefly discussed in this report.

In the past decades uranium production declined significantly in many regions. For example, the United States, Germany, France and South Africa have passed their peak production decades ago. The analysis shows further, that today's primary uranium supply (58,000 tU produced in 2012) is provided by only a few countries. In descending order, Kazakhstan, Australia, Canada, Namibia, Niger and Russia are the main players in this market, which together produce 85% of global uranium and hold two thirds of the resources. In contrast, about 30 countries consume uranium. Only Canada and South Africa are able to cover their own domestic demand. In recent years the demand of uranium for nuclear power plants amounted to about 70,000 tU per year. It was supplied from primary and secondary resources, with the share of secondary resources declining from a maximum of 50% in 1999 to 15% in 2012.

The strong production growth in Kazakhstan in recent years reduced the demand for secondary resources and took some pressure out of the uranium market. But, looking a bit further into the future, this production increase likely will be followed by a steep decline due to the depletion of the now operating mines. This output decline from Kazakh resources probably will start within the coming five to ten years. Once again, this will put pressure on the uranium market, which seems especially critical due to the long lead times for the development of new uranium mines of15 or even more years.

Another country of major relevance is Australia, which by far holds the largest reported resources. However, due to a limited potential for capacity expansion, these large resources rather provide a baseline for long lasting production, than for peak supply of uranium. The resources cannot be recovered in a reasonable timespan.

The global scenarios for the future uranium production reveal several challenges for the medium- and long-term supply of uranium. Based on current knowledge of mining plans an increase in global production can be expected in the coming years. This will be followed by a decrease in production somewhere around 2020 – in detail depending on, which resource category is seen as being recoverable. On the other hand, the long-term view of the uranium supply suggests, that with the currently identified resources future reactors based on uranium-235, can only be supplied with fuel for 40-60 years even at low growth rates of nuclear power. Nuclear high growth scenarios cannot be supported by uranium resources. They fail on two aspects, the ability to expand global mine capacity and the overall long-term availability of uranium. For no-growth or very low growth scenarios[4], the uranium demand seems coverable, at least in the short and medium term, under the assumption that beyond Reasonably Assured Resources also Inferred Resources are recovered in time.

Since the different scenarios essentially depend on the success of the currently planned mining projects, it appears quite possible that with an unfavorable development supply shortages or significant price increases can occur already in or prior to the year 2020, irrespective which IAEA growth scenario is considered.

Concerning unconventional resources, the extraction of uranium from seawater is likely to remain insignificant, as it would be very expensive and associated with high technical and energy expenditure due to the low concentration of uranium. The separation of uranium from phosphate ores already practiced 20 to 40 years ago enters the discussion again as the uranium content of fertilizers has increased in recent years and its removal must be performed anyhow. The technology of uranium separation is proven, but very expensive though new technologies are under development. Therefore, the by-production capacity of uranium will be determined primarily by the phosphate requirements. The maximum recovery rates were recently evaluated to 11,000 tons per year (about 15% of the current annual demand), if all phosphoric acid plants are upgraded with uranium separation technology. However, due to the maturity of many phosphate deposits, this capacity will shrink in the mid to long term and partly shift to China which still extends its phosphate production capacity. Nonetheless, about 3,000 to 5,000 tons uranium per year (5-7%) are expected in the short and medium term.

The reprocessing of fuel is limited in capacity and economically unattractive as the required removal of specific isotopes is challenging. In addition, the construction of new reprocessing plants is hampered by political and social reservations.

In a nutshell it can be stated that the nuclear industry does not only face long term supply restrictions due to limited uranium resources. It also has to face short and mid-term challenges to provide sufficient uranium for the currently expected nuclear capacity extensions as seen in IAEA growth scenarios.

[4] E.g. the EHNUR ISR scenarios in workpackage 3.

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Abbreviations

ads	adsorbed, adsorption
AGR	Advanced Gas-cooled Reactor
Am	Americium
ARMZ	AtomRedMetZloto, Russian Mining State Company
AUA	Australian Atomic Energy Agency
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Agency for Geo Sciences and Raw Materials)
BLEU	Blended low enriched uranium
BRD	Bundesrepublik Deutschland (Germany)
BWR	Boiling Water Reactor
CIS	Commonwealth of Independent States
CISAC	Center for International Security And Cooperation
cm	centimeter
Cm	Curium
Cs	Cesium
DMF	Dimethylefluoride
DoE	Department of Energy
EAR	Estimated Additional Resources
EPACT	U.S. Energy Policy Act
ERA	Energy Resources Australia Ltd.
EROEI	Energy return of energy invested
ESA	European Supply Agency
EU	European Union
EWG	Energy Watch Group
FR	Fast Reactor
FSU	Former Soviet Union
Gg	Gigagram
GW_e	Gigawatt electricity
HCL	hydrochloride acid
HEU	Highly Enriched Uranium
HNO_3	Nitric Acid
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
IR	Identified Resources
ISL	In-Situ Leaching
J	Joule
ISR	In-Situ Recovery
kg	Kilogram
KOH	Potassium hydroxide
Kr	Krypton
kt	Kilo tonne
kWh	Kilowatt hour
LEU	Low Enriched Uranium
LWGR	Light Water Graphite Moderated Reactor
LWR	Light Water Reactor

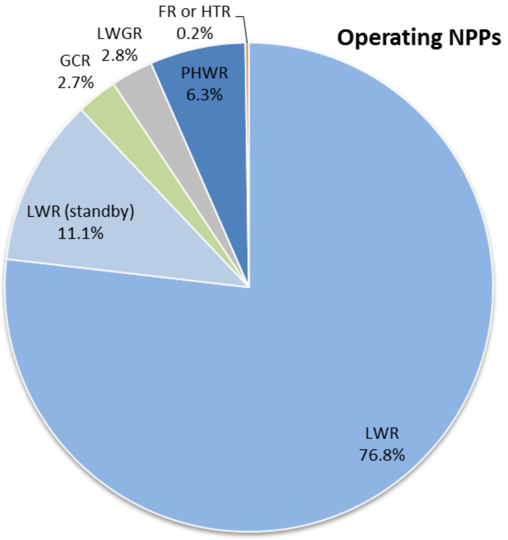
m	Meter
MeV	Megaelektronvolt
mg	Milligram
MJ	Megajoule
mm	Millimeter
MOX	Mixed oxide fuel
NEA	Nuclear Energy Agency
NNSA	National Nuclear Security Administration
Np	Neptunium
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
O	Oxygen
OP	Open Pit Mine
ppb	Parts per billion
ppm	Parts per million
Pu	Plutonium
PWR	Pressurized Water Reactor
PHWR	Pressurized Heavy Water Reactor
RAR	Reasonably Assured Resources
RBMK	Reaktor Bolschoi Moschtschnosti Kanalny, Russian "High Power Channel-type Reactor"
REE	Rare Earth Elements
RepU	Reprocessed Uranium
s	Second
Sr	Strontium
SWU	Separative Work Unit
t	ton
TBP	Tributhylenephosphate
TENEX	Tekhsnabexport, state owned Russian company for fuel service exports
Th	Thorium
ThDEPO	Thorium Deposits and Resources Data Base
tU	ton of uranium
TVA	Tennessee Valley Authority
TWh	Terawatt hours
TiO_2	Titanium Dioxide
USA	United States of America
USEC	U.S. Enrichment Corporation
U	Uranium
UDEPO	Uranium Deposits and Resources Data Base
UF6	Uranium hexafluoride
UG	Underground Mine
UK	United Kingdom
UOC	Uranium Ore Concentrate (“yellow cake”)
USD	US-Dollar
USGS	U.S. Geological Survey
USSR	Union of Socialistic Soviet Republic (today FSU)
U_3O_8	Uranium Oxide

U_{nat}	Natural uranium
U_{dep}	Depleted uranium
U_{eq}	Uranium equivalent
^{234}U	Uraniumisotope with 234 nucleons
^{235}U	Uraniumisotope with 235 nucleons
^{238}U	Uraniumisotope with 238 nucleons
WISE	World Information System for Energy
WNA	World Nuclear Agency
WOCA	World Outside Centrally planned economy Area
y	Year
$	US Dollar
%	per cent
°C	grad celsius

INTRODUCTION

To fight climate change and meet future energy demands on a global basis, new investments in nuclear energy are proposed by several institutions (IEA, IAEA). Even in a post-Fukushima world a constant growth of nuclear energy generation capacity is to be expected, at least in the developing economies of Asia.

For energy generation technologies fuel is one of the main aspects. Since the beginning of the nuclear era the main focus for the use of nuclear material in civil reactors was put on uranium-235 (^{235}U). Uranium reactors have almost 15,000 years of operating experience (WNA, 2012a) and are technically easier to implement than other fuel cycles. In addition uranium is less toxic than Plutonium and the "bomb aspects"[5] let it triumph over thorium. Figure 1 shows the distribution of reactor types in operation at the end of 2012 as well as all of those which were identified as planned or under construction in workpackage 3 of the project. Both figures show the major dependence of nuclear energy on ^{235}U now and in the coming decades, making up more than 99% and 96% of thermal reactor power respectively. Additionally it has to be taken into account that conventional ^{235}U reactors are based on proven technology, compared to alternative fuel cycles. Nonetheless a separate chapter is devoted to them (cf. Chapter 4).



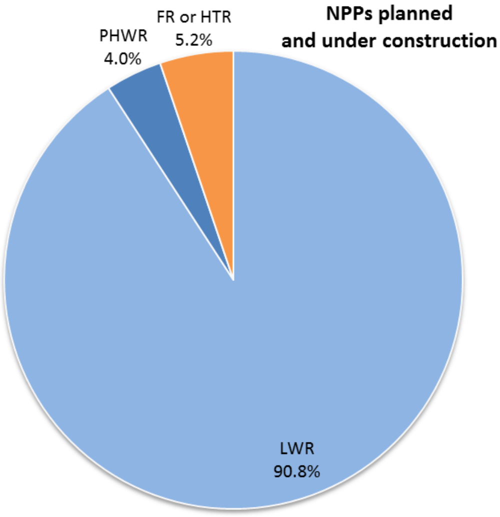


FIGURE 1: TYPES OF NUCLEAR REACTORS IN OPERATION AND PLANNED IN 2012 THE FIGURE IS BASED ON THE ISR 1 SCENARIO OF WORKPACKAGE 3. ALL THE REACTOR TYPES EXCEPT FR AND HTR (CF. ABBREVIATIONS P.10) RELY ON URANIUM 235 AS FUEL. THE PLANNED HTRS ARE CURRENTLY ALSO DESIGNED FOR URANIUM FUEL, THE FRS ARE PLUTONIUM FUELLED.

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[5] Concerning this Martin (2009) states: *"Weinberg and his men proved the efficacy of thorium reactors in hundreds of tests at Oak Ridge from the '50s through the early '70s. But thorium hit a dead end. Locked in a struggle with a nuclear- armed Soviet Union, the US government in the '60s chose to build uranium-fueled reactors — in part because they produce plutonium that can be refined into weapons-grade material. The course of the nuclear industry was set for the next four decades, and thorium power became one of the great what-if technologies of the 20th century."* The better proliferation resistance of Thorium is currently under discussion. Ashley et al. (2012) recently identified simple chemical pathways to open up proliferation possibilities.

The main focus of this report is to present collected data on the global long term "uranium situation". This is of special interest as nuclear energy tends to bind large resources and current reactor designs are planned to operate 60 years, standing in contrast to market-oriented aspects of the fuel cycle, which are usually (comparatively) short.

As secondary supplies are limited by their availability (stocks) and technical/economic feasibility (e.g. reprocessing), the medium and long term fuel supply for a uranium-235-based reactor fleet has to be provided by primary uranium (directly mined).

For this report an analysis of the current market situation has been made. Uranium resources, frame conditions for uranium production and a secured supply have been evaluated. Based on this, scenarios were created to show the capabilities of long-run uranium supply compared to a bandwidth of future demand provided by the IAEA. The production scenarios are based on recent production and estimates future production by taking into account mining development and expansion plans of producing countries, while using different categories of confidence for the resource estimation (Reasonably Assured and Identified Resources).

Note that IR is used as abbreviation for Identified Resources in this report, not for Inferred Resources as done by e.g. the IAEA!

METHODOLOGY

The evaluation of uranium resources and supply is an issue spanning the whole globe. As an in-situ evaluation of this global uranium situation is impossible to perform within one project in terms of time and costs, the most reasonable approach to complete the task of the workpackage was the analysis of available literature, the participation at relevant conferences and meetings as well as stake- and shareholder interviews.

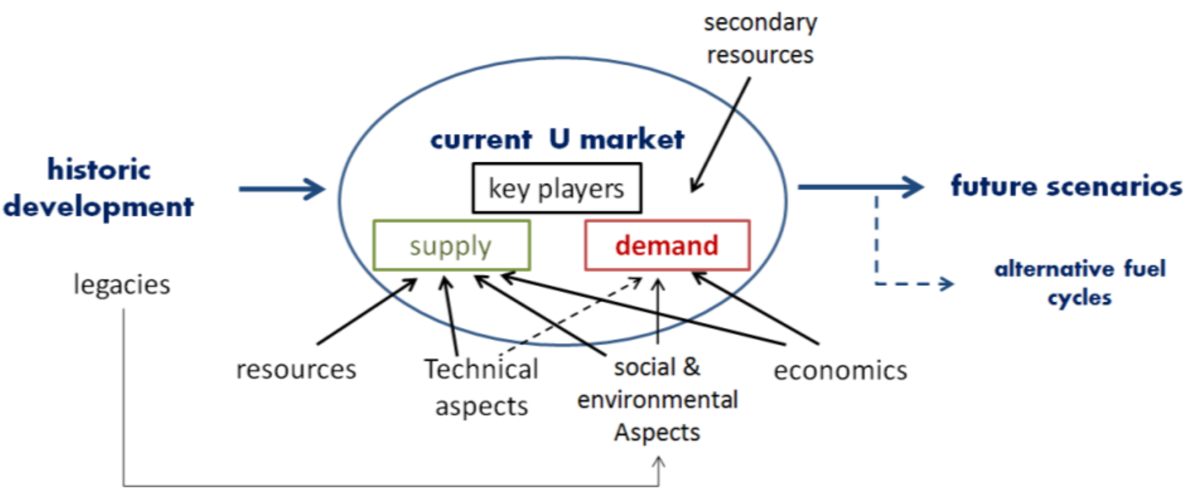

FIGURE 2: MINDMAP URANIUMSUPPLY

To carry out a comprehensive assessment of the world's uranium resources and resulting availabilities, it is necessary to understand the current market situation and its interconnections. An extended research on available literature was performed to identify stakeholders, major producers (countries or companies) as well as historical trends and expectations for the uranium market. A large database was established containing information on countries and mines and related resources, historical production trends and issues, expected expansions and other relevant data. In addition frame conditions for market development as well as technical and socioeconomic restrictions were evaluated.

Main source of information was the uranium industry itself, where information on mining and uranium resources was obtained from annual reports, technical reports, websites and press releases. An additional source of information was the International Atomic Energy Agency (IAEA) particularly via the biannual joint IAEA/OECD publication “Uranium: Resources, Production and Demand” (e.g. (OECD-NEA / IAEA, 2012, 2010)) also known as Redbook. It includes global views on uranium resources as well as detailed insights on specific countries, as far as the information is provided by those states. Various geological services and the World Nuclear Association (WNA) were assessed as other reliable data source. In addition technical reports and scientific papers were assessed to complete the picture for the technical state of the art, the processes within the fuel cycle and alternative sources for nuclear fuel.

All data evaluated was collected in a database which was used to create figures and scenarios. A list of the literature supporting this database can be found in Annex I. The data covers historic and recent aspects of the uranium fuel cycle on a global and a country basis such as resource estimates, gathered from the different Redbook-Editions, uranium production figures, production capacities and capacity projections, demand and demand projections, exploration expenditures.

In addition detailed information was obtained for depleted, operating and planned uranium mines. The data includes time of deposit discovery, deposit type, geographic location, start of production, delays in startup, (planned) end of production, reserves and resources, grades, historic production figures, capacities, mining plans and any additional information, that could be gathered.

On the basis of the collected data, resources were analyzed and evaluated in a bottom-up manner. Assorting resources located in different deposits resulted in identification of most important (prospective) mines and regions. In the next step comprehensive synopses of theses mining facilities provided conclusive country specific, as well as global pictures of future production scenarios. Furthermore uranium was not only adduced quantitatively, but also classified via its characteristics, for example the ore quality (grades), mining costs or uncertainties of resource estimations. Historical data gives an insight into trends of production, prices and exploration as well as capacity utilization.

To facilitate the view of the figures for the reader, a color code was used throughout the work. Information related to

- Australia is green,
- Canada is blue,
- Kazakhstan is purple,

- Namibia is aquamarine,
- Niger is orange,
- Russia is red.

In addition the colors yellow (USA), pink (South Africa), and brown (China) were kept throughout the work. In few cases exceptions from this color code had to be made for practical reasons.

SUPPLY SCEANRIOS

The supply scenarios were commenced via analyzing single mines and deposits. Production outlooks for the main mining centers were created using resource data, planed capacities and company mining plans. For 60 historic, operating and planned uranium production centers detailed profiles (e.g. Figure 3) were created on the basis of different resource categories and capacity load factors. Global figures were assembled for capacity loads of 80% for the different mines, as the global average has been between 70 and 80% over the past decades (cf. Figure 6). Depending on resource category and available data, 50 – 70% of global resources have been accounted for in this detail. In addition to the mining profiles, small deposits and resources, reported to the IAEA by its member states, which could not be assorted directly to existing or planned mines, were approximated via logistic growth profiles (Hubbert, 1956) and could therefore be added to the figures of the different resource categories to complete the global picture. A similar approach was already made in 2006 by the Energy Watch Group (Zittel and Schindler, 2006), using bell-shaped curves to analyze global resources. Although in reality limitations of the market and the infrastructure apply, the description via bell-shaped curves is expected to be a useful approximation and is fairly well in line with historical production curves.

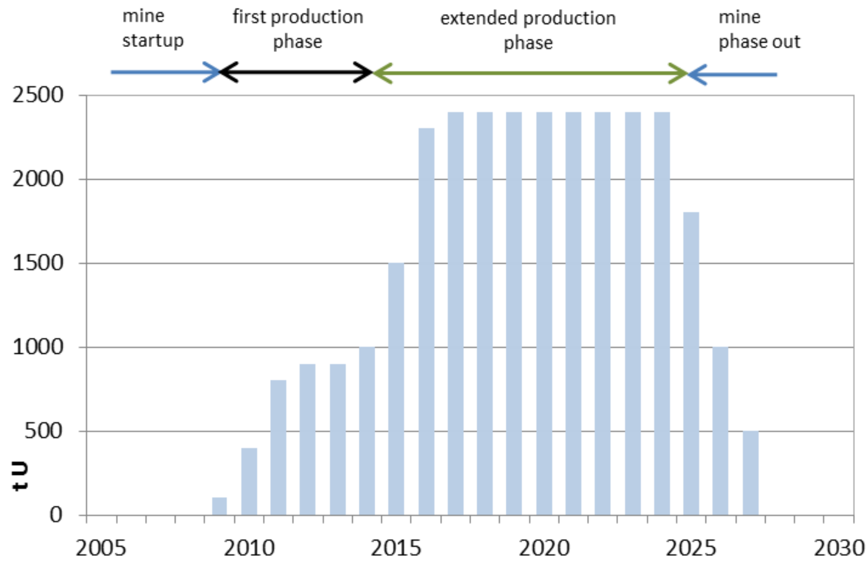

FIGURE 3: EXAMPLE OF A PRODUCTION SCENARIO FOR NORTHERN KHARASAN 1 INCLUDING AN EXTENSION OF PRODUCTION TO 3000 TU P.A. AT 80% CAPACITY.

Via the summation of single production scenarios, outlooks for various countries as well as global scenarios for different resource categories were generated, which were compared with and related to future uranium demand scenarios. As a result an insight on the fuel supply capability for current and planned reactors could be provided.

The comparison of scenarios created with a reference date in the end of 2008 and the end of 2012 reflects the changes in the situation of the global uranium market due to the impacts of the Fukushima accidents.

LIMITATIONS

In contrast to most commercial applications, this work targets towards a long term view of uranium supplies, which is afflicted by uncertainties by its nature. Some of the figures presented in this work cover a timespan until 2100. Although the nuclear energy generation covers long timespans in many aspects, planning is usually not done more than five to ten years ahead, except maybe when constructing a large nuclear reactor and calculating is pay-off. This is especially true for small or medium-sized uranium mines with an operating time of 10 – 15 years. Thus the long-term views (from 2040 and later) presented can by no means be understood as projections, but rather a way to point out frame conditions for a long term uranium supply such as

- the necessity to replace large mining capacities in a relatively short time-span if old mines are depleted and uranium-235 fueled nuclear power shall play a major role at this time
- the limitations in recovering uranium from large deposits in a reasonable timespan,
- or to visualize, that the reach of a resource is not simply the resource base dived by the demand.

A large uncertainty lies in the development of the resource base. It can be expected that, new discoveries are going to be made as well as rising prices may result in additional uranium being economically mineable and one has to allow for some economic based argumentation that increased prices may lead to lower cut-off grades, accessibility of lower grade ores, more efficient use and other aspects (WNA, 2012b) and therefore a larger resource base. Still, there is no guarantee for those resources being accessible in future. For historical production it has been shown, that even for the most reliable class of resources the full amount of uranium could never be extracted (Dittmar, 2011). Additionally it can be assumed that the best ore already has been extracted in the past, so quality, production rate and economic competiveness has to be expected to decline, resulting in lower future mining efficiency. The author considers the current resource estimates to be a reasonable, low-risk basis for future scenarios. Beyond that, it has to be noted that during the course of the work it became apparent, that other aspects may have a larger impact on the supply of uranium than the resource basis, especially in the short and medium term.

Today uranium is being mined in 22 countries. Although there are several uranium mines in operation, only a small number has a large share in the global production. The Top 10 mines made up

52% of production in 2011 (WNA, 2013a), followed by about 20 mines with another 30%. Thus these production centers are essential for current production and only 30 mines need to be considered to cover more than 80% of the global uranium mining.

Most of these mining facilities are located in only six countries, Australia, Canada, Kazakhstan, Namibia, Niger and Russia, which accounted for 85% of the total production in 2012 (WNA, 2013b). A look at the resources of these states reveals that they also hold the major amount of the global resources. Thus these countries and their mines were analyzed in detail for this project; smaller mines in other countries are less relevant for the global picture and their future development was approximated with the Hubbert-approach (cf. p. 16).

Another important aspect is that the quality of data from different sources was quite diverse. Some companies[6] provide very detailed data on mines and properties relating to resources, capacities, expansion plans and so forth. On the other hand some major players of the uranium market publish relevant data only rudimentarily, nevertheless enough to identify trends and capacities in the respective countries. This concerns especially the CIS-countries, which tend to provide meager data on their resource situation, as long as only state owned companies are involved. Additionally these countries have used other resource classifications historically, making comparisons of estimates not always easy. Some assumptions had to be made to create reasonable supply scenarios:

- Kazakhstan: Eighteen mines are in operation at the moment. For ten of those mines only “overall resources” could be identified. As these mines are already in operation and it seems unrealistic to assume they don’t have any Reasonably Assured Resources (RAR) and exclude them from the respective scenarios. Thus an average RAR to Identified Resources ratio of 0.45 was derived from the remaining eight mines and applied for the RAR-basis of the mines with less detailed data.
- Russia: A similar approach was made for the Russian Elkon deposit. 45% of the Resources were accounted as RAR.

To have an up-to-date picture of uranium resources and the production scenarios, it was strived to find and use the most recent data (end of 2012). To assure comparability of data and reporting dates – especially the Redbook reference date January 1st, 2011 – any changes which occurred since then were considered and accounted for when creating production scenarios. A cross-comparison of data and sources was carried out to ensure the highest accuracy of data, wherever applicable, resulting in some discrepancies. These were found to be mostly due unclear definitions of resources and reserves, undefined reporting dates or accounting/not accounting for recovery factors. In few

[6] The provision of resource figures by companies might bear some risks as well. So far no cases of resource related fraud are known for uranium, but have happened in the past with gold (cf. http://en.wikipedia.org/wiki/Bre-X)

The 2.4 billion euro loss of the French company Areva in 2011 was mainly related to the takeover of African uranium deposits, which now might never produce uranium. Investigations did not uncover any fraud attempts (Reuters, 2012).

cases it was not clear where the discrepancies came from. Thus the values that seemed most reliable and precise were chosen by the authors for further processing.

Finally there are several other inhibitors for uranium production, which contain the major uncertainties and will constrict future production capabilities the most (OECD-NEA / IAEA, 2010). These comprise problems in technical implementation, political frameworks, socio-economic conflicts or geographical distribution.

1 HISTORIC AND CURRENT SITUATION OF URANIUM SUPPLY

1.1 BASICS ON URANIUM, URANIUM PRODUCTION AND ITS USE IN NPPS

Uranium is a radioactive heavy metal, which is quite abundant in earth's crust, with an average concentration of 0.00014% or 1.4 ppm (WNA, 2006). It can be found in various and complex minerals, of which pitchblende (U_3O_8) is most relevant for mining. Within the geological forming processes of the earth, uranium was distributed unequally and sedimented in different formations. There are several different geological types of deposits, of which high-grade unconformity related and sandstone deposits are currently primarily mined. While ore concentrations can reach up to 20% of U_3O_8, economically extractable concentrations begin at approximately 0.03%. While deposits of high concentration account for a small share, the majority of global uranium is found in unconventional resources (less than 0.01 % U) (Deffeyes and MacGregor, 2001).

TABLE 1: NATURAL URANIUM ISOTOPES (BINDER, 1999)

Isotope	Natural Abundance	Half-life
^{238}U	99.2745 %	$4,468 * 10^{9}$ a
^{235}U	0.7200 %	$7,038 * 10^{8}$ a
^{234}U	0,0055 %	$2,455 * 10^{5}$ a

Natural uranium is a mixture of the three isotopes ^{238}U, ^{235}U and ^{234}U (see Table 1), of which ^{238}U is the by far most common. Today uranium is used mainly for energy generation in nuclear reactors. The bulk of these reactors require an increased share of ^{235}U and thus the uranium has to be enriched before fuel is fabricated. This results in up to nine tons natural uranium needed to produce one ton of fuel, including losses and depending on enrichment grade (WISE, 2013a), resulting also in a slightly larger overall uranium demand than for reactors operating on non-enriched uranium. Table 2 shows the enrichment and the amount of uranium used by different reactor types per year. Note that also the reactor generation and the burn-up influence the uranium demand (also refer to Table 3 in (Krymm and Woite 1976) and Tables 2.11 & 5A.1 in (OECD-NEA / IAEA, 2012).

TABLE 2: URANIUMENRICHMENT FOR DIFFERENT PURPOSES

Type	Enrichment	NatU requirements [tU/GWe/yr]	Petajoule electrical from 1t NatU*
Heavy Water Reactor	(Almost) none	145 - 170	0.2
Gas-cooled Reactor (Magnox, AGR)	2,5 – 2,9 %	unknown	0.13 – 0.14
Light Water, Graphite Moderated Reactor (LWGR, RBMK)	2.4 %	unknown	0.13
Boiling Water Reactor (BWR)	3 – 3.2 %	165 -210	0.14 – 0.18
Pressurized Water Reactor (PWR)	3.6 – 4.2 %	165 -220	0.14 – 0.18

*Does not include energy necessary for enrichment. Electricity gained per tU can be expected to be lower for older reactors, but no data is available.

There are three common methods to extract uranium from its deposits[7]: Open Pit Mining, Underground Mining und In-Situ-Leaching. The decision, which method to choose for extraction, is based on the properties of the orebody (size, dimension, rock type …) and economic considerations.

Open Pit Mining (OP) is preferably used for near-surface uranium deposits. The easy accessibility allows for rapid removal of the ore. This method requires a large area for the pit itself and the tailings, especially at low ore grades, and thus has a large environmental impact (see Figure 5).

Underground Mining (UG) is used to mine deep deposits several hundred meters below surface. While it shows much less impact on the surface, high uranium concentrations are required to make it economically feasible and the exposition of workers can be expected to be higher. In both cases – the OP and UG mining – the recovered ore is the processed in a uranium mill. The ore is shredded and the uranium separated via chemical processes. The recovered Uranium Ore Concentrate (UOC) – often referred to as yellowcake – is then shipped to the subsequent facilities of the nuclear fuel cycle.

The In-Situ Leaching (ISL) – also called In-Situ Recovery (ISR) – involves no movement of ore at all. The principle of this technique is to dissolve the uranium in the rock formation, transport it to the surface in a liquid and separate the mineral afterwards. The groundwater, which is mixed with either an acid or a base, is used as solvent. Prerequisite for the feasibility of ISL is a permeable, water-saturated deposit (e.g. sandstone), which is bounded by an impermeable layer at the top and bottom. Due to the wide distribution of sandstone deposits, the low investment costs and the reduced impact on the surface, this method of mining is increasingly gaining popularity.

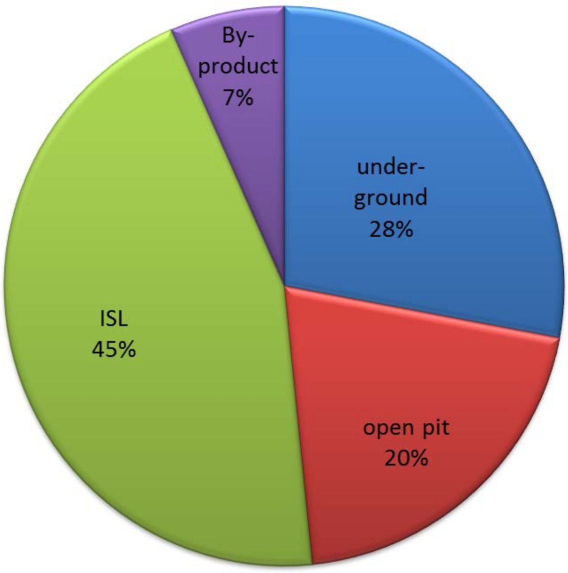

FIGURE 4: URANIUM PRODUCTION BY METHOD IN 2012 (DATA: WNA, 2013B)

Another method, which is important at the moment due to the large Olympic Dam deposit, is the production of uranium as by-product. In the by-product recovery uranium is extracted alongside with other metals. This can of course only be practiced at multi-metal deposits and allows for low-grade uranium to economically mineable.

The choices of mining method as well as the grade of the ore have a large influence on the resources that can be actually recovered and the amount of uranium ore concentrate, which can be produced. This can be about 95% of the initially identified resources for high grade, open-pit or

[7] For detailed information on Uranium production methods see (IAEA, 2001a).

underground mines or only 65% in by-product extraction. The recovery factor of ISL ranges between 70 and 80%.

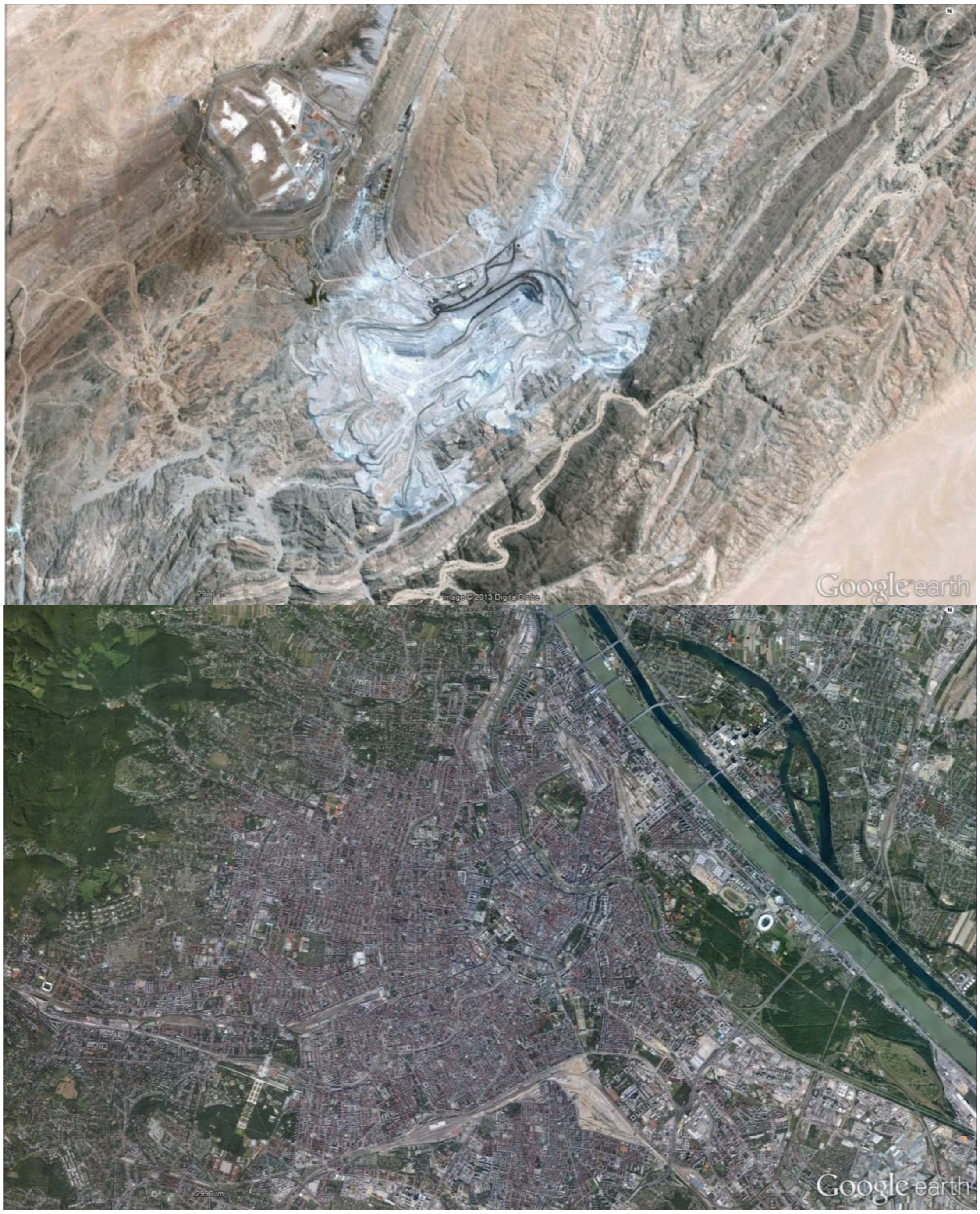

FIGURE 5: AREAL VIEW OF THE ROSSING URANIUM MINE, NAMIBIA AND THE CITY OF VIENNA, AUSTRIA AT THE SAME SCALE. (GOOGLE EARTH, ©GOOGLE INC.)

1.2 HISTORICAL DEVELOPMENT AND CURRENT STATUS OF URANIUM DEMAND AND SUPPLY

The history of uranium production has seen different trends so far. In the Fifties a first boom was driven by the development of weapons of mass destruction. The startup of increasingly more commercial nuclear power plants and the expectations for nuclear growth came along with a second rise in worldwide uranium production, which had its maximum in 1979. The global uranium mining output was far beyond the needs at that time, resulting in a total overproduction of about 600,000 tU[8]. At the end of the cold war the status on the market changed. Uranium stocks from the USSR, which got available to the market, as well as downblending from weapon grade uranium to reactor-grade uranium lead to a decrease in demand and price of uranium. This resulted in a reduction of the primary supply (uranium directly from mining) to far below requirements in the past 20 years (Figure 6), with the rest of the demand being covered by uranium from stocks, weapons and to a small extent from reprocessing. In the past years the share of secondary resources went down from a maximum of 50% in 1999 to 15% in 2012.

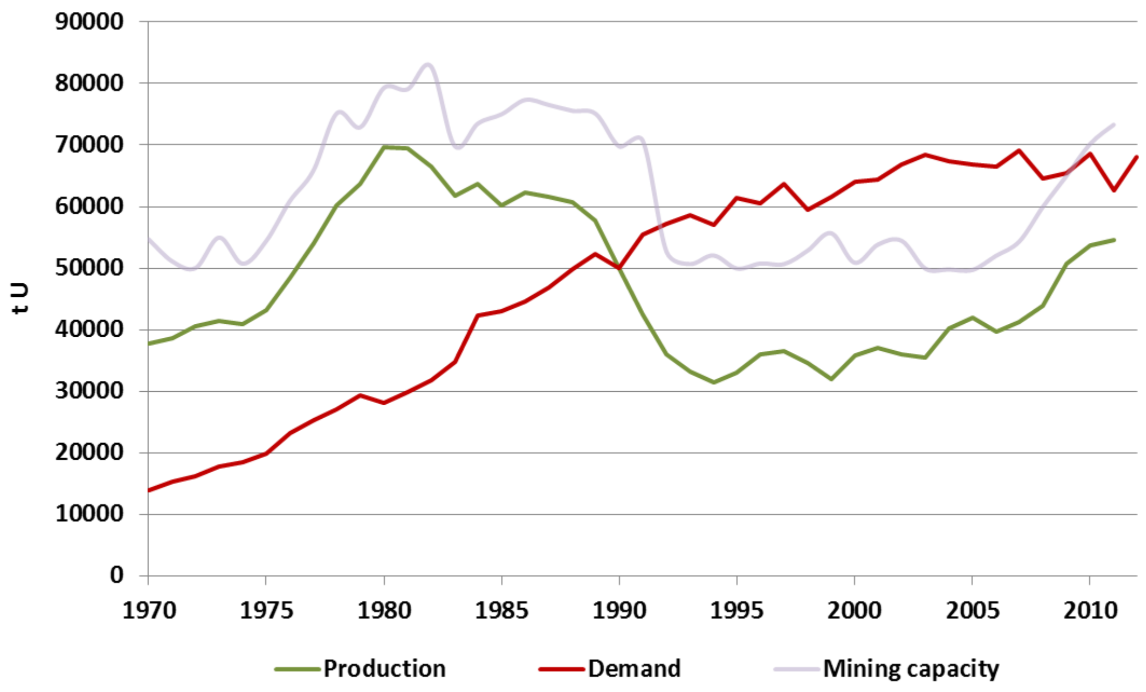

FIGURE 6: HISTORICAL DEVELOPMENT OF URANIUM REQUIREMENTS, PRODUCTION AND PRODUCTION CAPACITY

In 2007, probably driven by the expectations of a large nuclear renaissance and the flooding of the Cigar Lake mine, an almost exponential increase of the uranium price occurred. Although the impact on the nuclear industry was rather small, the exploration work triggered by the high prices resulted in a 15% increase of the estimated uranium resource base (Wikipedia, 2013a).

[8] Details on these "Secondary Resources" are content of chapter 2.4.

In 2011 the accidents in Fukushima also had their impact on the uranium demand, due to 50 Japanese and eight German reactors (temporarily) shut down.

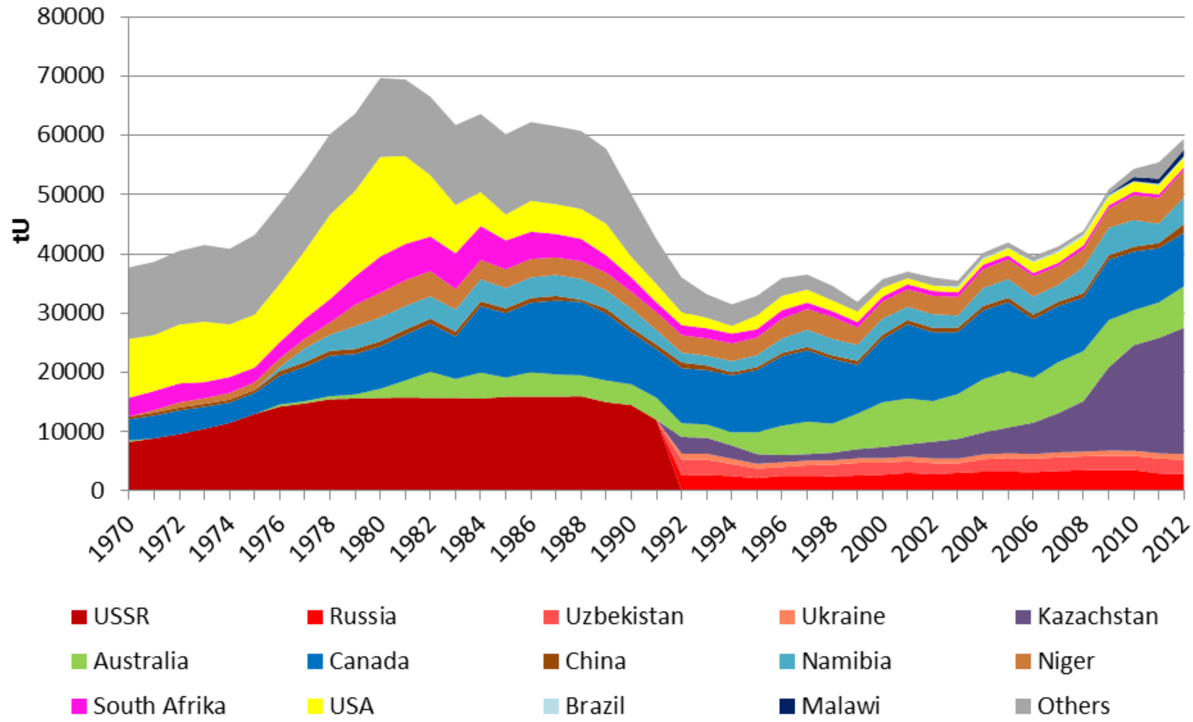

FIGURE 7: HISTORIC URANIUM PRODUCTION BY COUNTRY

At the beginning of 2013 there were 391 nuclear reactors in operation (not accounting for the temporary Japanese shutdowns) relying on uranium-235 as fuel. In 2012 these reactors required roughly 68,000 tons of uranium (WNA, 2013c)[9], of which about 85% (58 300tU) could be directly met from mining, while the rest had to be covered from secondary resources. The major uranium producers were Kazakhstan (21300 tU), Canada (9000 tU) and Australia (7000 tU). Malawi produced more than 1000tU the first time in its history. Other countries that produced more than 1000 tons of uranium in 2012 were Niger, Namibia, Russia, Uzbekistan, the USA and

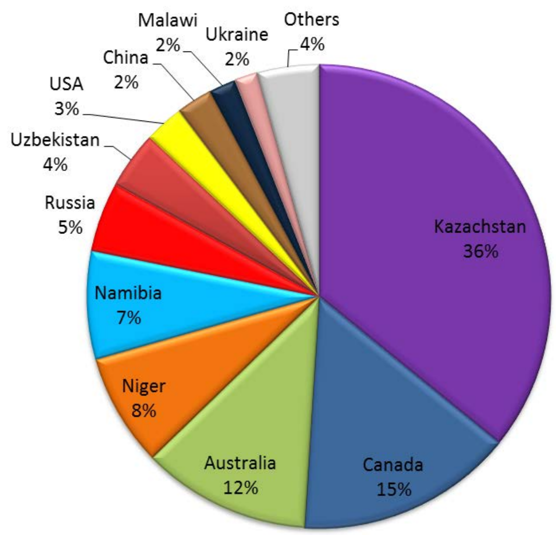

FIGURE 8: DISTRIBUTION OF 2012 URANIUM PRODUCTION

[9] The amount of uranium acquired is not necessarily equivalent to the amount loaded into the reactor. Some stocks may be built up or be used by the utilities.

(maybe[10]) China. The mentioned countries mined more than 95% of the global uranium in 2012, the first six mined 85%. In contrast about 30 countries consume uranium at the moment. Only Canada and South Africa can cover their own domestic demand (cf. Figure 25).

The distribution of companies involved shows a similar picture as for the countries. Ten companies have a share of 91 percent on world uranium production in 2012 (Figure 9). Figure 10 shows the 15 largest production sites in 2012, accountable for almost two thirds of the global output.

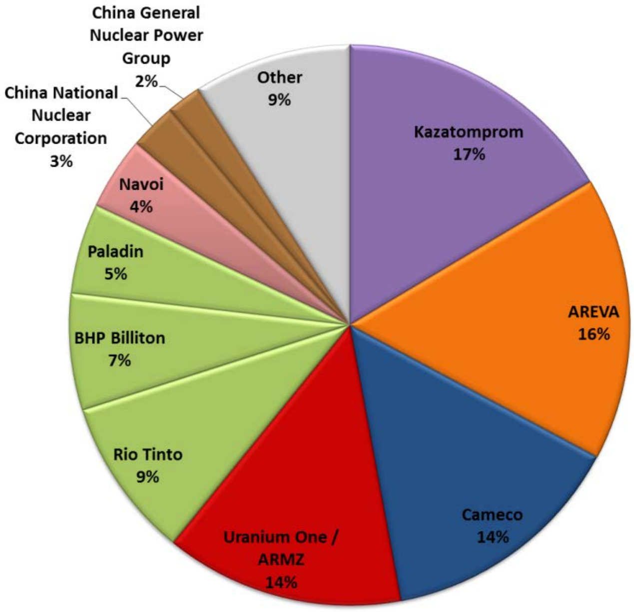

FIGURE 9: COMPANIES INVOLVED IN URANIUM PRODUCTION AND THEIR SHARE IN GLOBAL PRODUCTION [11] (Areva, 2013, p. 70)

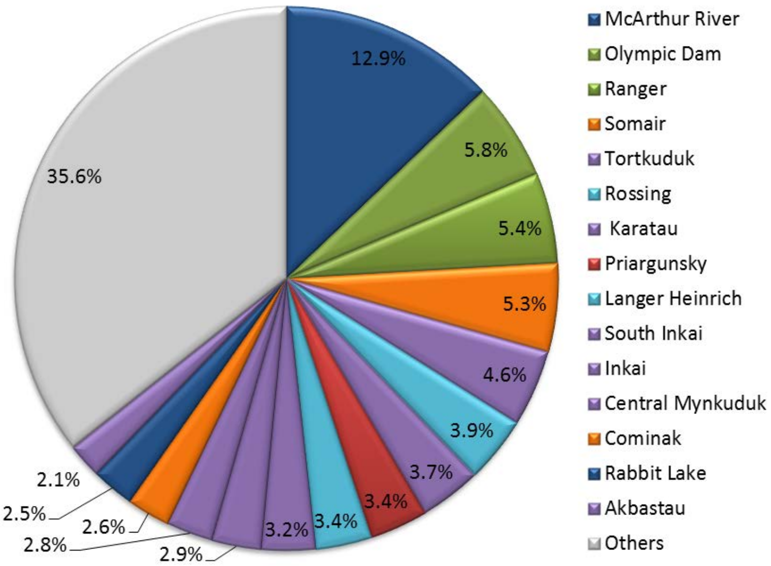

FIGURE 10: THE 15 LARGEST URANIUM MINES AND THEIR SHARE ON GLOBAL PRODUCTION IN 2012 (WNA, 2013B).

[10] Production data received from China is afflicted with uncertainties. At the moment China is less focusing on acquiring foreign assets, than rather expanding domestic production.

[11] The colors represent the companies' head offices. Areva is actually based in France, but mined 36% of its uranium in Niger.

In 2012 once again - and as expected - Kazakhstan was the largest uranium producer. The production figures of about 21,000 t U were 8% above the 2011 production (19,400 tU).

Uranium production has made an impressive growth over the past years and at the moment the country is the main (sole) contributor to closing the gap between production and demand. From 2000 to 2010 the production could be increased tenfold, mainly via In-Situ-Leach mines. The production in 2010 (18,000 t U) even outnumbered the very ambitious development plan of the state-owned company Kazatomprom to extend the uranium mining output to 15,000 t by 2010 (Figure 11). Looking at the upcoming projects and the growth rates of the last two years it seems probable, that the further target set in the early years of this century, to reach a production of 30,000 tons by 2015, will not be reached.

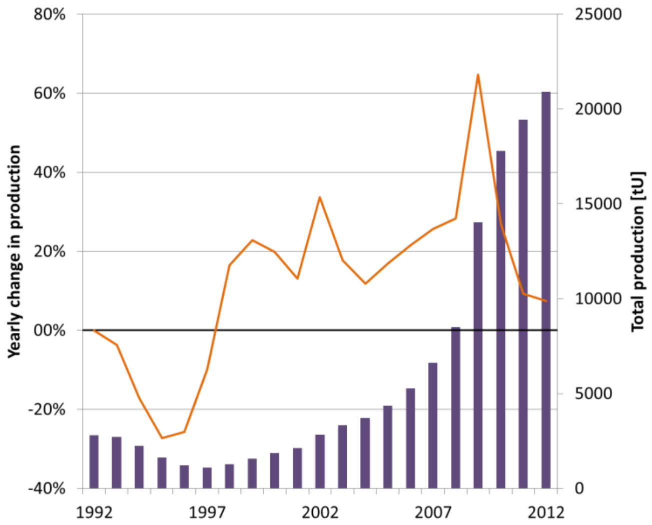

FIGURE 11: HISTORICAL DEVELOPMENT OF KAZAKH URANIUM PRODUCTION

2 AVAILABILITY OF URANIUM

As for any other valuable resource, it is of interest for uranium ores, how they have been distributed in the earth's crust and in what quantity they have accumulated. The IAEA database "World distribution of uranium deposits" (IAEA, 2012) and to some extent the Uranium Redbook try to create a worldwide total collection of data on uranium deposits[12]. Such global coverage was accompanied by the usual problems of an integrated approach. On one hand, there are data for the different regions of the world in different quality, on the other hand resources of each country are classified and defined in other ways.

This chapter deals with the availability of uranium from different sources and the state of global distribution. Generally, geological uranium resources can be divided into two categories. Conventional Resources on one hand are those that get mined in a well-proven way via open-pit, underground or In-Situ-Leach mining. On the other hand there are Unconventional Resources, which can be found in large amounts but very low grades, like uranium from seawater or phosphates.

The current understanding of Conventional Resources is what is also called Primary Uranium, which is the one currently directly mined and supplying the uranium market. Secondary Uranium, simply put, is uranium that has been mined a longer time ago (maybe was also changed in its composition) and is now treated to be used as fuel.

2.1 PRIMARY URANIUM RESOURCES

2.1.1 DEFINITION OF RESOURCE CATEGORIES AND RECOVERABILITY

The estimates on uranium resources are based on worldwide exploration work. The term "resources" thereby refers to the available amount of a commodity. The clearer the outer parameters are defined within the exploration work, the more certain a defined amount of uranium may be recovered. Within the industry the uranium deposits are differentiated due to the reliability of the estimates of their content and subdivided into classes of recovery costs. The method to classify the uranium resources is the following[13].

- **Identified Resources (IR)** is the sum of two classes of resources with different levels of confidence: Reasonably Assured Resources[14] and Inferred Resources. They are subdivided into 4 cost categories: <40 USD/kgU, <80 USD/kgU, <$ 130 USD/kgU and <$

[12] A "uranium deposit" is defined as an amount of naturally occurring mineral that is mined at present or can be expected to be mined in future.

[13] This classification, used by the IAEA (OECD-NEA / IAEA, 2012, p. 461), is the internationally the most established. For example Areva (Areva, 2013) reports in its Annual Report 2012: *"In 2010, the AREVA group decided to comply with international standards for the classification of its resources and reserves. As of today, 97% of the resources and 95% of the reserves are consistent with the standards, compared with 88% and 33% respectively at the end of 2011."*

[14] Reasonably Assured Resources correspond to Economically Demonstrated Resources for Australia and the Reserves A & B for Russia.

260 USD/kgU. They include the comprehensive total cost of uranium production like direct mining, transportation and processing costs, as well as environmental and waste management or other related costs.

- *“**Reasonably assured resources (RAR)** refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably assured resources have a high assurance of existence. Unless otherwise noted, RAR are expressed in terms of quantities of uranium recoverable from mineable ore.”*

  The RAR are subdivided into **Measured Resources** and **Indicated Resources.**

- *“**Inferred resources (IR)**[15] refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit’s characteristics, are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.”*

- Furthermore a category of **Undiscovered Resources** is defined, which includes **Prognosticated** and **Speculative Resources**. The latter are expected to be found in regions with similar geological conditions as the Identified Resources, are afflicted with large uncertainties and not considered in any of this work’s scenarios.

- **Reserves** (Areva, 2013, p. 72): *“Economically and technically recoverable share of measured or indicated resources, as demonstrated by at least one preliminary feasibility study or mining project. The study includes adequate information about mining and processing operations, metallurgy, the economic aspects and other relevant factors to demonstrate that mining is profitable at the that time the report was written. Mineral reserves include dilution factors and the allowance for mining losses incurred during mining operations.”*

  The Reserves are subdivided into **Proven** and **Probable Mineral Reserves.**

It is essential to keep in mind that the resources identified in situ do not comply with those recoverable. Within the technical processing chain there are losses to be accounted for, which can be anywhere between 5% and 50%, depending on the method of mining. The following estimates on

[15] Note that IR is used as abbreviation for Identified Resources in this report! Inferred resources were previously called Estimated Additional Resources (EAR).

global resources already account for those losses corresponding to the experiences at the respective mines or deposit types. It also must be kept in mind that the classification according to cost classes is more qualitative, but does not coincide with the specified cost-numbers as these obey inflation rules and vary over the years.

2.1.2 STATUS OF RESOURCES

As of 1st of January 2011 about 4.4 million tons of natural uranium were defined as reasonably assured and minable at costs below 260 USD/kgU by the IAEA-member states. Those RAR are distributed very unequally, with more than 90% being located in only eleven countries (Figure 12). In the category of <130 USD/kgU, more than 90% of the resources are located in only ten countries. Most of these states can also be found among the major uranium producers and can mostly be considered as rather politically stable.

About 27% of global RAR are located in Australia, of which more 80% can be allocated to the Olympic Dam deposit, thus hosting more than 20% of the global RAR. The United States, Canada and Kazakhstan reported the second, third and fourth largest amount of RAR, with 472,000 tU, 420,000 tU and 402,000 tU respectively. While Australia, Canada and Kazakhstan are also large produces, the output in the USA is rather low because of higher production costs. Seven other countries reported more than 100,000 t of Reasonably Assured Resources at the end of 2010. These are Brazil, China, Namibia, Niger, Russia, South Africa and the Ukraine.

Adding inferred resources to this evaluation has no major influence on the global picture. Almost 90% of the Identified Resources – 7.1 million tons in total – can be found in 11 countries. Australia possesses more than a quarter of these resources; 18% of the global amount is found at Olympic Dam.

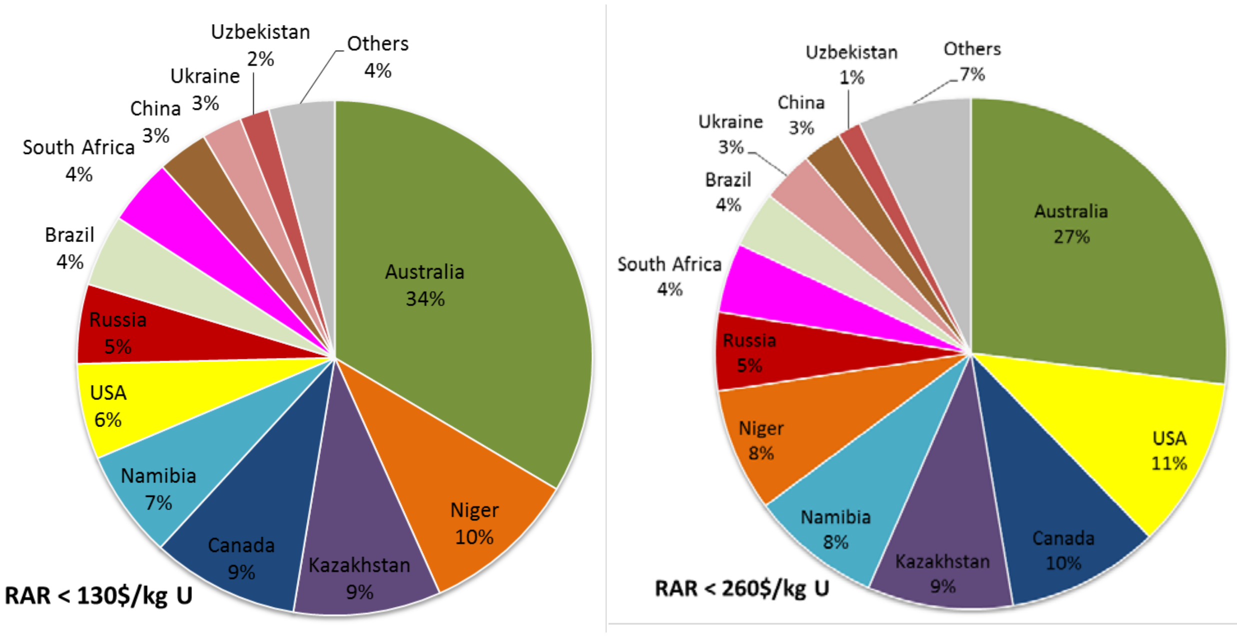

FIGURE 12: GLOBAL DISTRIBUTION OF REASONABLY ASSURED RESOURCES DATA:(OECD-NEA / IAEA, 2012)

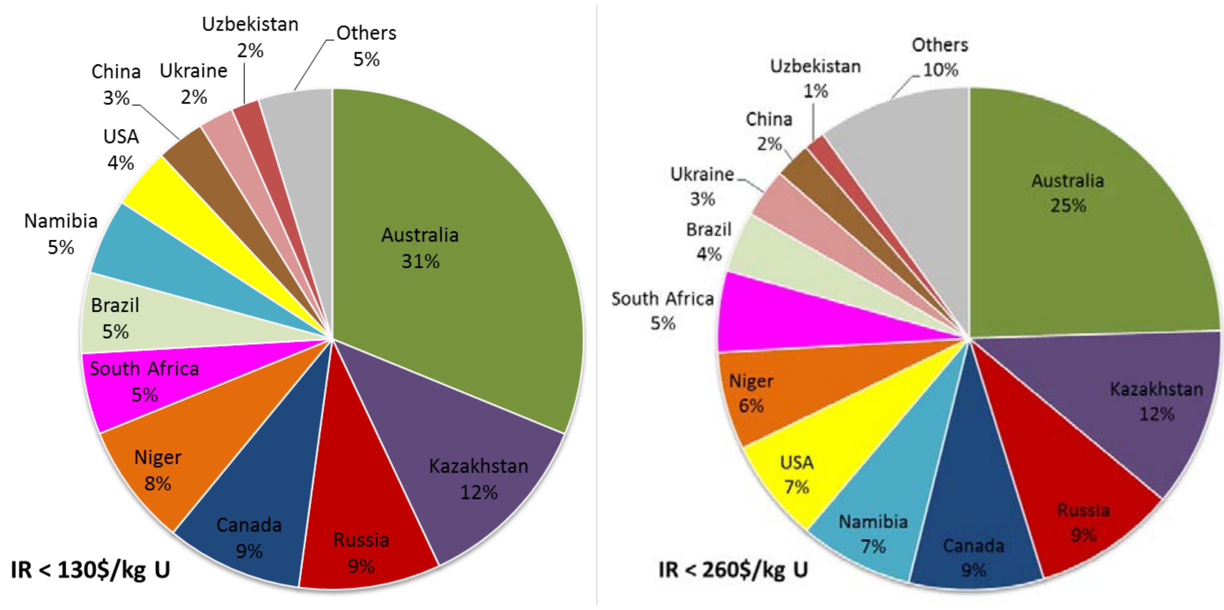

FIGURE 13: GLOBAL DISTRIBUTION OF IDENTIFIED RESOURCES DATA:(OECD-NEA / IAEA, 2012)

2.1.3 DEVELOPMENT AND UNCERTAINTIES OF RESSOURCE DATA

A first look at the global resources over the past decades actually reveals a constant growth of Reasonably Assured Resources. Since the beginning of systematic collection of data in the Redbooks in 1970, the RAR increased from 1.2 to 4.4 million tons, while additional 2 million tons were used in reactors. Also for the Identified Resources a more or less steady growth can be observed, except a downgrade in the early 1980s resulting from a major re-evaluation of US and Canadian inferred resources (Figure 14). The growth of resources looks promising for the future supply of reactors at a first glance. Yet it has to be mentioned, that the number of countries, that reported their resources, changed since 1970 and some additional countries have been added over the course of time, to give some impact on global resources. In particular, the first addition of the uranium of the former Soviet Union to the global resource picture in 1995 resulted in a rather large leap. If the same countries are used as a basis for evaluation of resource development (Figure 15), there is no growth, but rather a decline of uranium resources in most states. Only Australia shows growing resources in recent years and this almost exclusively to one mine (Olympic Dam). In the case of Identified Resources the 2009 numbers are below those of 1977 and 1979 for the selected countries.

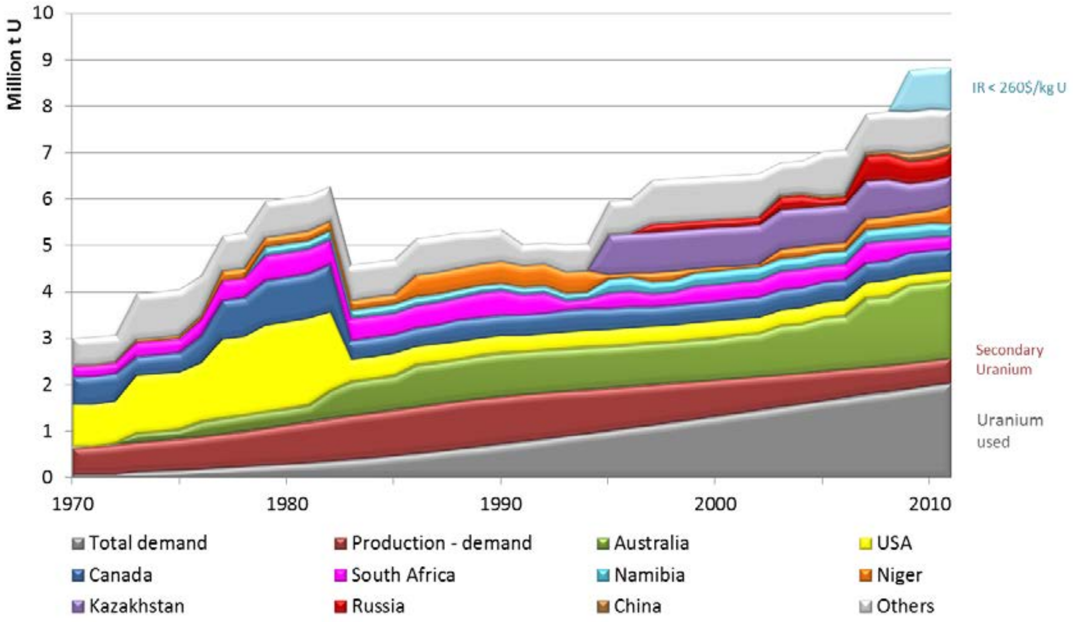

FIGURE 14: HISTORICAL DEVELOPMENT OF IDENTIFIED RESOURCES.

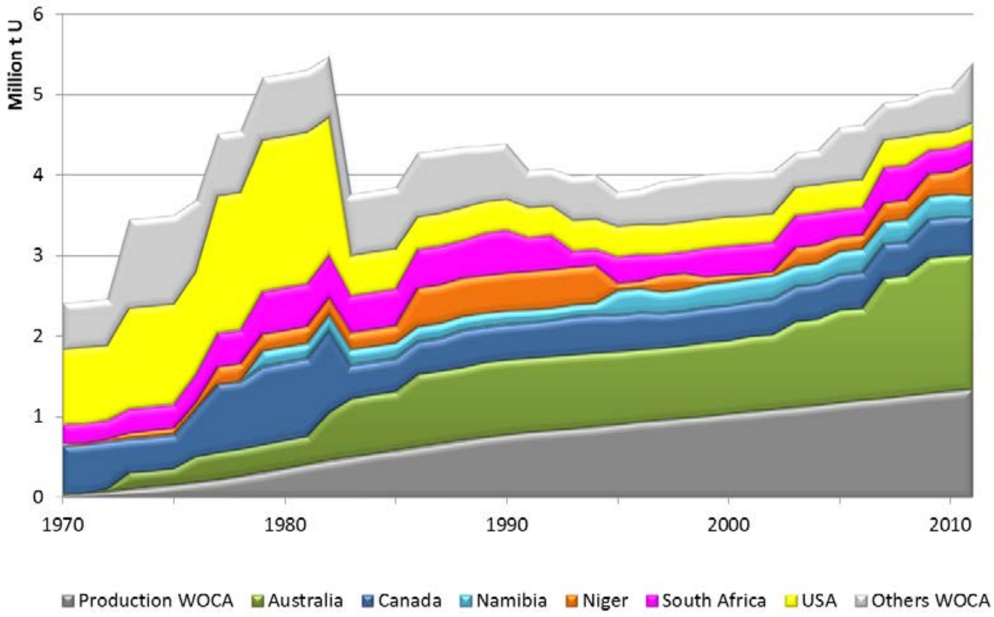

FIGURE 15: HISTORICAL DEVELOPMENT OF IR <130 USD/KGU, WORLD OUTSIDE CENTRALLY PLANNED ECONOMY AREA (WOCA).

The main changes in recent years are limited to an increase of the Australian resource basis and re-evaluation of resources to higher cost categories in many other countries. This resulted in the introduction of a new cost category (<260USD/kgU) in the 2009 Redbook (Figure 14). This shift can also be seen in Figure 16. Roughly ten percent of the global resources (RAR and IR) are in the lowest cost category. The RAR < 80 USD/kgU were at the same level in 2011 and 1999. Major resource growths occurred within the Identified Resources and the high-cost RAR. Nonetheless it has to be mentioned that 580,000 tons of uranium were produced from 1999 to 2011, while about 680,000 tons of resources were transferred from the IR to the more secure RAR in the 130USD/kgU category.

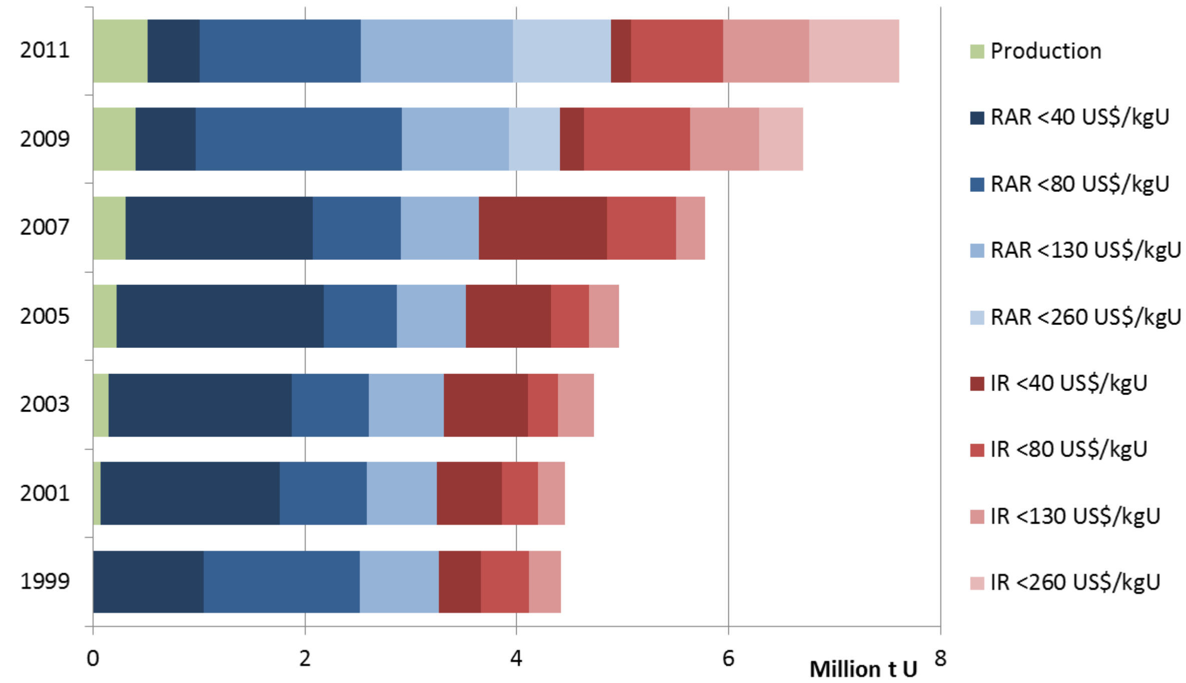

FIGURE 16: DEVELOPMENT OF RESOURCES IN DIFFERENT RESOURCE AND COST CATEGORIES FROM 1999 TO 2011

Besides the limitations in the data set, the resource classifications contain uncertainties as well. For historical production it has been shown, that even for the most reliable class of resources the full amount of uranium could never be extracted (Dittmar, 2011). Additionally it can be assumed that the best ore already has been extracted in the past, so quality, production rate and economic competiveness has to be expected to decline, resulting in lower future mining efficiency.

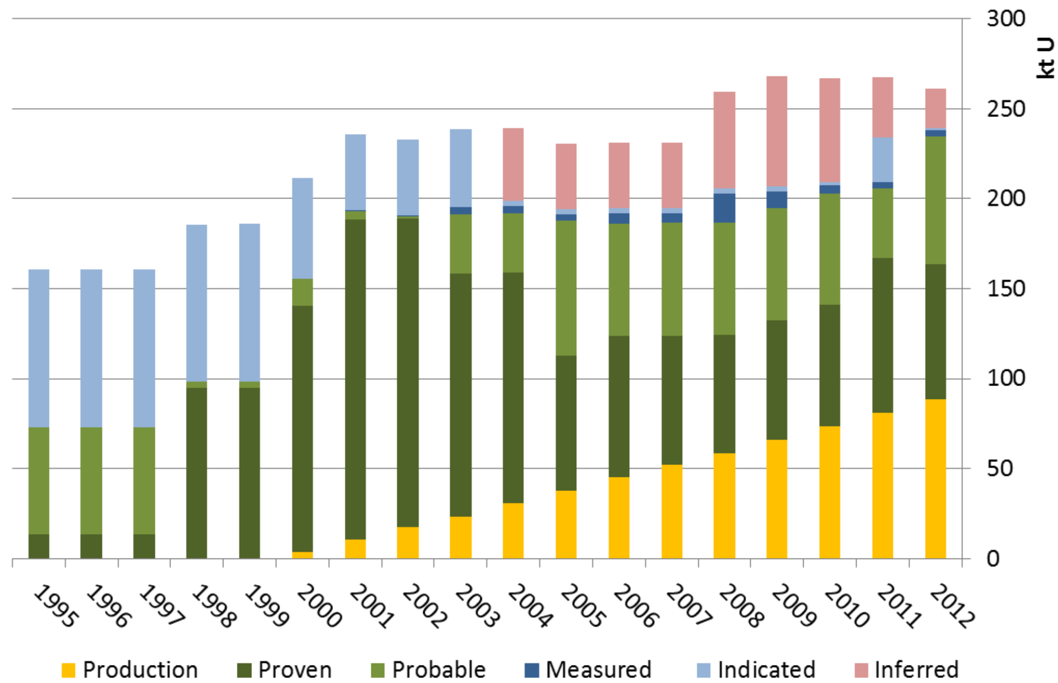

FIGURE 17: MCARTHUR RIVER CHANGES IN RESOURCE ESTIMATIONS

Analysis of company data shows not only resource but also reserve data can be uncertain. Figure 17 shows the development of the reserve and resource estimates of McArthur River by its operator Cameco from 1995 to 2012. It shows shifts of the reserves and resources within the different categories of confidence.

These uncertainties are also reflected in the companies' assessments and often stated in their annual reports or websites:

"Mineral Resources that are not Mineral Reserves do not have demonstrated economic viability. Inferred Mineral Resources have a great amount of uncertainty as to their existence and as to their economic feasibility. Under no circumstances can it be assumed that all or any part of an Inferred Mineral Resource will ever be upgraded to a higher Mineral Resource category or converted to Mineral Reserves." (Uranium One, 2013)

"The group's uranium reserves and resources are only estimates drawn up by the group based on geological assumptions (developed based on core drillings, among other things) and economic assumptions, and there is no guarantee that mining operations will produce the same results. The group could be led to modify these estimates if there is a change in evaluation methods or geological assumptions, and/or a change in economic conditions. …….. It is not possible to guarantee that the projected quantities of uranium will be produced or that the group will receive the expected price for these ores, which is indexed to market performance, in accordance with contract terms agreed upon with the customers. There is no assurance that other resources will be available. Moreover, uranium price fluctuations, production cost increases and declining mining and milling recovery rates can affect the profitability of reserves and require their adjustment." (Areva, 2013)

These uncertainties on resource estimates have an influence on supply side but shall not be overemphasized, as other factors might have a bigger impact on the future supply with uranium. They shall be discussed in the following chapter.

2.2 FRAME CONDITIONS FOR THE PRIMARY SUPPLY WITH URANIUM

Already in 1980 the Survey of energy resources (BGR, 1980) stated, that the prevalent but not justified assumption, that the resources would equal the available supply quantity, is one of the fundamental misconceptions among users of these terms. Parameters like economic issues, availability of capital and labor, the physical nature of the deposits, environmental problems and long lead times are ignored.

2.2.1 EXPLORATION, DISCOVERIES AND DEVELOPMENT OF CAPACITIES

The methods for detection of uranium deposits similar to those of other raw materials, but also include some specific aspect due to the radioactive nature of the material. Usually the search for uranium is started in areas with geological formations as previously discovered[16]. Exploration is started using aerial or ground geophysics and geological surface surveys (Areva, 2012). If a larger

[16] If not trying to explore new uranium provinces, companies prefer to explore areas relatively cose to existing deposits or mines, as the necessary infrastructure and knowledge is already in place.

occurrence of uranium is assumed first drillings are performed to get an estimate on the resources. The estimates are refined by tighter drilling and finally a study is made to confirm the technical and economic feasibility. The overall duration of this process is ten to fifteen years and it is accompanied by official approval processes all along. The mining can start after a concession is granted, which is usually done in pilot scale.

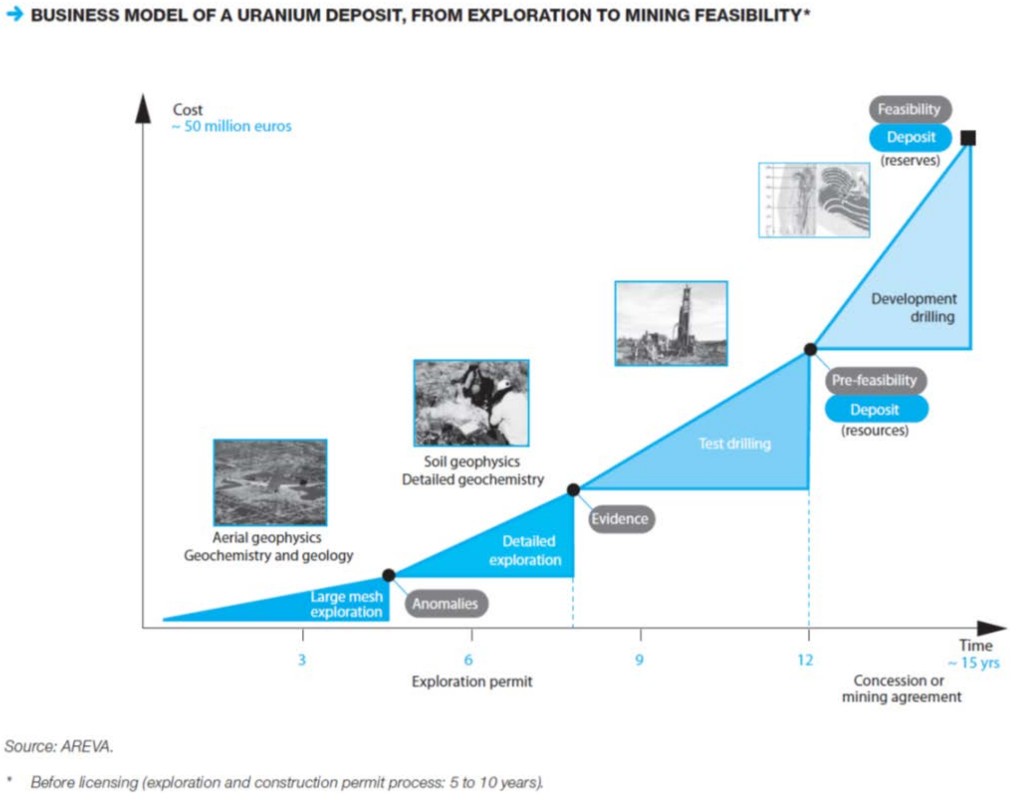

FIGURE 18: TIMEFRAME FOR THE EXPLORATION AND EVALUTION OF RESOURCES AT A URANIUM DEPOSIT © ARVEVA (AREVA, 2013)

During the last years – driven by a long production deficit and rising demand – exploration has experienced a large boost, which led to a substantial increase of Identified Resources since the beginning of the century (OECD-NEA / IAEA, 2010). The main exploration work however is done on two geological types of deposits (unconformity-related and sandstone deposits), or on improvement of estimates for known deposits. Hence the increase of resources is rather based on reevaluation of existing deposits, founded on higher uranium prices, or exploration work in the proximity of know deposits and rarely on identification of new uranium provinces. This is shown exemplary for Australia in Figure 19. The figure shows the development of the overall Australian resources from the 1960s onwards (green bars). To account for uranium that has already been extracted, the cumulative production was added to these resources (blue). Finally the 2009 resources were backdated to the year of the initial discovery of the respective deposits (e.g. the 2009 resources of Olympic Dam are represented by the red bar in 1975). This shows that most of the Australian resources have been discovered prior to 1975 and an increase in resources occurs due to reevaluation of know deposits and changes in cut-off grades respectively[17].

[17] A lower cutoff grade (see p. 33) may result in more resources recoverable from a deposit.

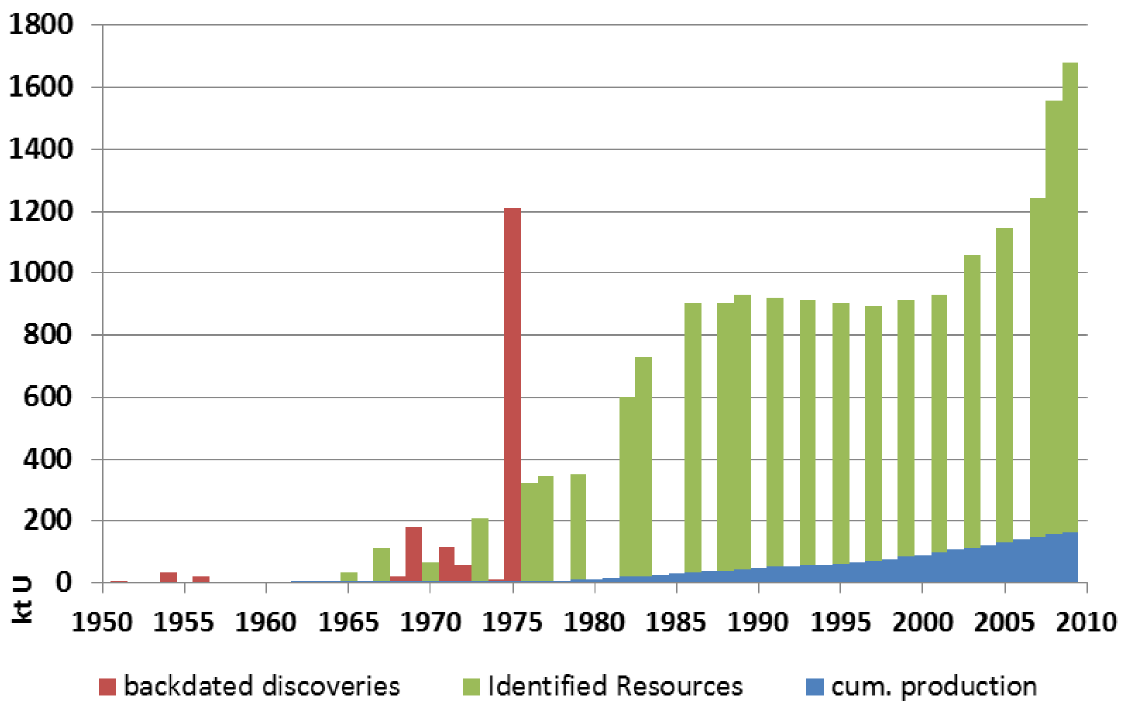

FIGURE 19: HISTORICAL DEVELOPMENT OF AUSTRALIA'S IDENTIFIED URANIUM RESOURCES. THE RED BARS BACKDATE THE RESOURCES TO THE YEAR OF DISCOVERY OF THE DEPOSIT.

Another important aspect, concerning development of capacities in the uranium mining business, is that the time span from the discovery of a deposit to the production startup can be even longer than the 10 to 15 years mentioned above. It has been constantly growing in the last decades and amounts to some 25 to 30 years for some recently opened or developing production centers (Figure 20). The OECD/NEA assumes the main reasons for this increase to be the following (OECD-NEA / IAEA, 2006a):

"(i) The easiest deposits to develop had already been put into production by 1975;

(ii) Increasingly stringent environmental constraints and regulations have added significantly to the timeframe between discovery and the start of mining.

(iii) The impact of generally depressed uranium market prices during the past three decades has contributed to delays in starting new mines as has competition from secondary supply such as inventory drawdown and HEU from dismantling of nuclear weapons, which reduced demand for primary supply."

Due to the increasing uranium prices and demand, it can be assumed that these lead times can be reduced in the near future. Nevertheless durations of 10 – 15 years[18] have to be expected for countries with well-developed regulatory regimes to take a deposit in operation.

[18] Hall and Coleman (2013, p. 2) assume an average of 15 to 20 years from discovery to production and some 15 years from deposit delineation to mining (p. 35)

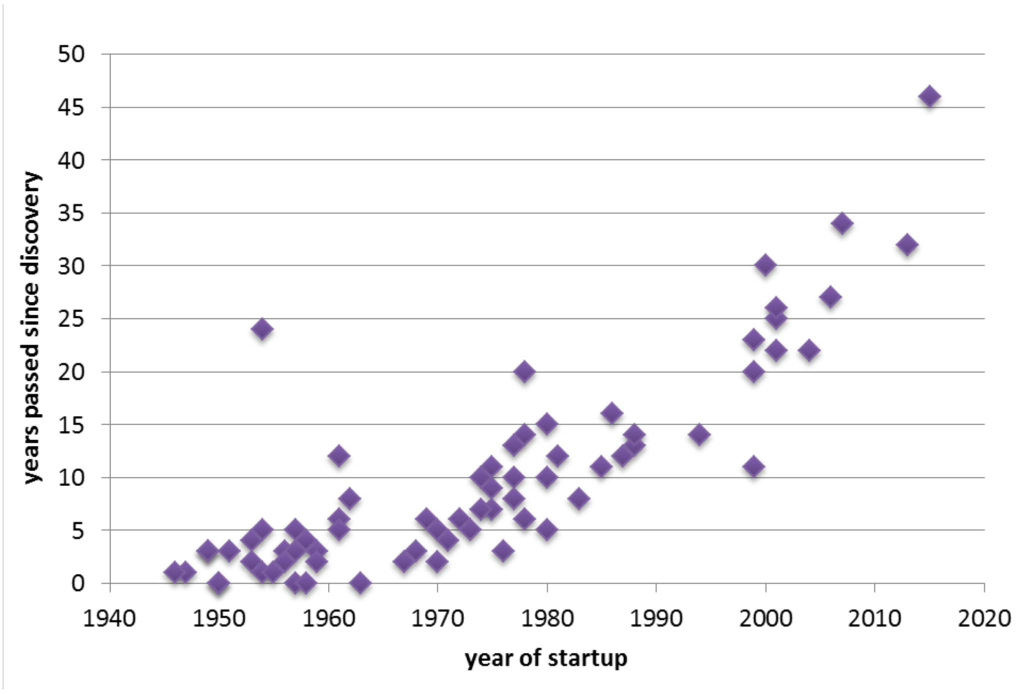

FIGURE 20: HISTORICAL DEVELOPMENT OF THE TIMESPAN BETWEEN MINE DISCOVERY AND STARTUP. SOURCE: "THE REDBOOK RETROSPECTIVE" (OECD-NEA / IAEA, 2006A) EXPANDED BY MORE RECENT DATA, INCLUDING ESTIMATED STARTUPS FOR IMOURAREN (2015) AND CIGAR LAKE (2013).

At last one has to consider, that projects sometimes don't advance as planned. Figure 21 shows the delay startup of mines recently opened or to be opened. The figure was created by looking through the Redbook editions from 1999 to 2011, finding the first date planned for startup and comparing it to the actual startup or now planned startup. The average delay from 42 mines was 2.4 years. This might even be a bit longer, as 11 of these production centers have not yet started operation.

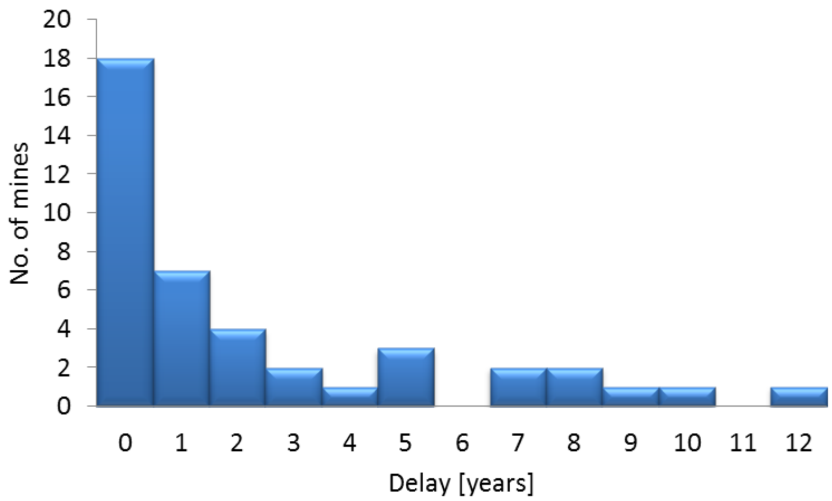

FIGURE 21: DELAY OF MINE OPENINGS BASED ON DATA FROM THE REDBOOKS 1999 TO 2011.

2.2.2 TECHNICAL AND INFRASTRUCTURAL ASPECTS

The abovementioned delays in startup often have their cause in problems of the technical implementation or infrastructure. This not surprising, as uranium production centers can reach huge dimensions (cf. Figure 5) requiring electricity, fuel, water, chemical components and other materials in suitable amounts, as well as the hauling of waste rock and transportation of (interim) products. All of this has to be secured before and during operation and mostly in remote regions. The following paragraphs shall point out some issues which occurred in past years, delaying the development of mines.

At the **Russian Khiagda** deposit pilot ISL production had been in progress since 1999, while planning to develop full scale capacities starting in 2005 (OECD-NEA / IAEA, 2006b). As of 2008 the project website (ARMZ, 2008) stated: *"The start of full-scale construction used to be held up by an insufficiently developed production and transportation infrastructure: the absence of a bridge spanning the Vitim River, the need to rebuild the road to the ore field and to build a railroad base in Chita."* It finally took until 2011 to complete the construction on all production facilities. As for now it is planned to reach full capacity production of 1800 tU in 2019 (ARMZ, 2012).

The example of the Canadian Cigar Lake Project exemplifies technical issues, which may occur during uranium mining. The updated report of the Energy Watch Group (EWG, 2013) summarizes the events at the mine as follows:

"The construction of the uranium mine at Cigar Lake was originally planned to start in early 2005 and last for 27 month. Production was planned to start in early 2007. After two water inflows which occurred in April and October 2006 a third inflow took place during the dewatering of the mine in 2008. This was caused by a fissure in the 420m tunnel. In October 2009 that inflow was remotely sealed with an inflatable seal and then filled with concrete and grout. Since the 420m tunnel is not part of the future mine as originally planned, it is now planned to abandon this tunnel filled it completely with concrete. Early in 2010 the dewatering was completed. Remediation and underground construction work has commenced since then. The underground construction is estimated to be 70 percent completed and production is currently planned to start in late 2013. If no further delays occur the mine will start to produce uranium ore almost 6 years behind original schedule. The lifetime of the mine is estimated to be 15 years with full production volumes between 2016 and 2027."

The delay of Cigar Lake had heavily impacted the expected Canadian (and global) uranium production. Over the past years the country's production has rather declined than grown, as it was expected 5 -10 years ago.

Other difficulties affecting uranium production were reported from **Australia** in the past years. Heavy rainfalls in late 2010 and early 2011 flooded the open pit mine Ranger resulting in a suspension of the plant processing operations (ERA, 2012). Thus the mine output decreased by 30% two years in a row (3216 tU in 2010 and 2240 tU in 2011). Operations recovered to 70% of the mines capacity (3146 tU) in 2012. In 2010 a haulage system was damaged at the Olympic Dam mine. The system operated at 25% for some months, resulting in a significantly lower output than the years before (BHP Billiton, 2011).

The rising share of ISL mining goes along with an increased demand of sulfuric acid[19] and the availability of acid can now be seen as critical for uranium operation. In 2008 **Kazakhstan** missed its target to be the world's largest producer for the first time through the following event (WNA, 2013d): "*A fire at a sulfuric acid production plant in 2007 led to shortages, and due to the delayed start-up of a new plant, rationing continued until mid-2008. Extra supplies were sought from Uzbekistan and Russia, but uranium production well into 2009 was affected. Uranium One revised its 2008 production downwards by 1080 tU, which it said was "primarily due to the acid shortage" for its South Inkai and Kharasan projects (70% and 30% owned respectively) which were just starting up. In August 2009 Cameco reported that production at Inkai would remain constrained through 2009 due to acid shortage.*"

2.2.3 URANIUM ORE GRADES

One of the main parameters defining a uranium deposit is the grade, concentration of uranium in the ore, which is very relevant for the economics of uranium mining. The concentration below which it is not economically feasible to mine is called cut-off grade. The cut-off grade is determined in a feasibility study and has to consider various impacts influencing the financial outcome, such as infrastructure, development, mining operations or taxes. Thus cut-off grades can be very different, and usually range between 0.01 and 0.05 % (100ppm to 500ppm). As the cut-off grade is linked to the price, it has to be noted, that with increasing price a lowered cut-off grade may increase resources as long as this is not hampered by other impact factors.

Figure 22, created by Jan Willem Storm van Leeuwen (van Leeuwen, 2006), shows the estimated distribution and amounts of uranium by grade in the earth's crust and water in a double logarithmic scale. It can be seen at a glance that the high concentration deposits account for a rather small proportion, while the bulk of global uranium resources are found in concentrations below 100 ppm U (unconventional resources). Around this grade Storm assumes an energy cliff (van Leeuwen, 2012), which is the point where more energy is used to over the nuclear life cycle than is gained in a nuclear power plant. Applying his theory of the energy cliff to the currently known resources, results in a depletion of resources in 40 to 60 years. His work was criticized for using to high energy input values for the nuclear life cycle, and is not quite clear why this would also apply to ISL, as no ore is moved. Nonetheless it makes sense for conventional mining, even if this cliff might be somewhat lower. Further one has to bear in mind that ISL mining comes at the cost of lower recovery factors and the share of recoverable uranium declines with lower ore grades.

[19] Between 3 kg and 80 kg of sulfuric acid per kg U depending on the orebody, making up for a relevant share of the operating costs (WNA, 2013d).

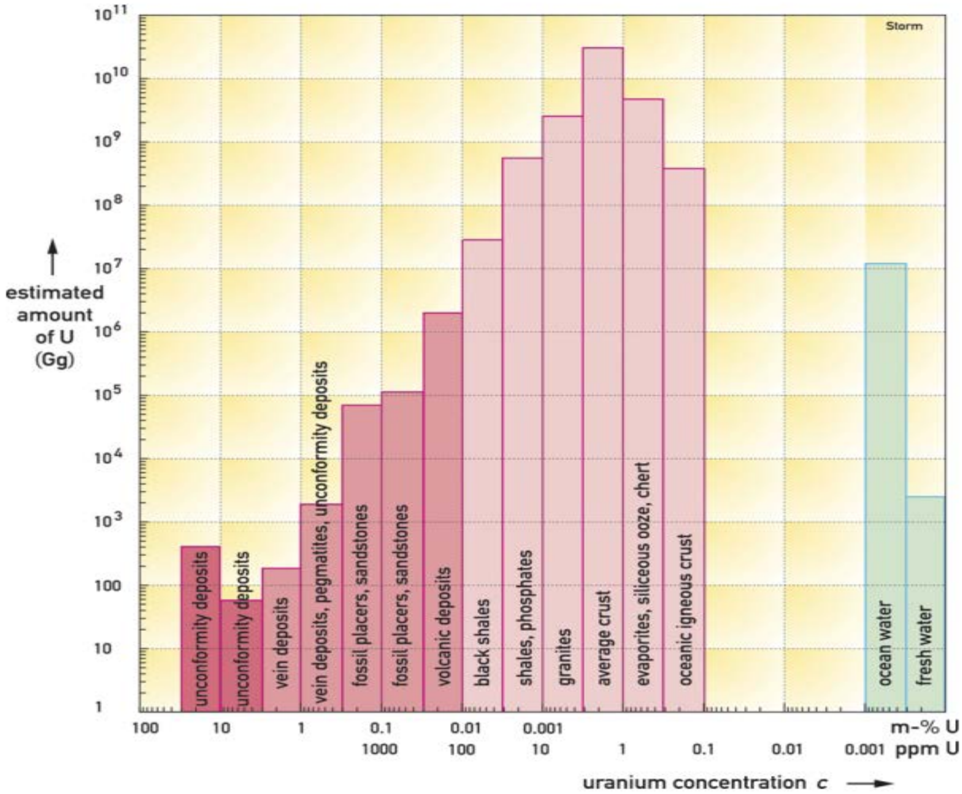

FIGURE 22: DISTRIBUTION OF URANIUM ON EARTH BY GRADES © STORM VAN LEEUWEN (VAN LEEUWEN, 2006)

Figure 23 shows the global distribution as identified in the IAEA Uranium database in 2010 (IAEA, 2012). The figure includes already mined uranium and less explored deposits, so the overall numbers do not exactly accord to the Redbook resources. Historically higher grade deposits were mined (red), while today most mines operate in the range below 0.2% (except the Canadian mines). Also the bulk of the resources can be found below that grade, even if not accounting for operating mines and thus Olympic Dam.

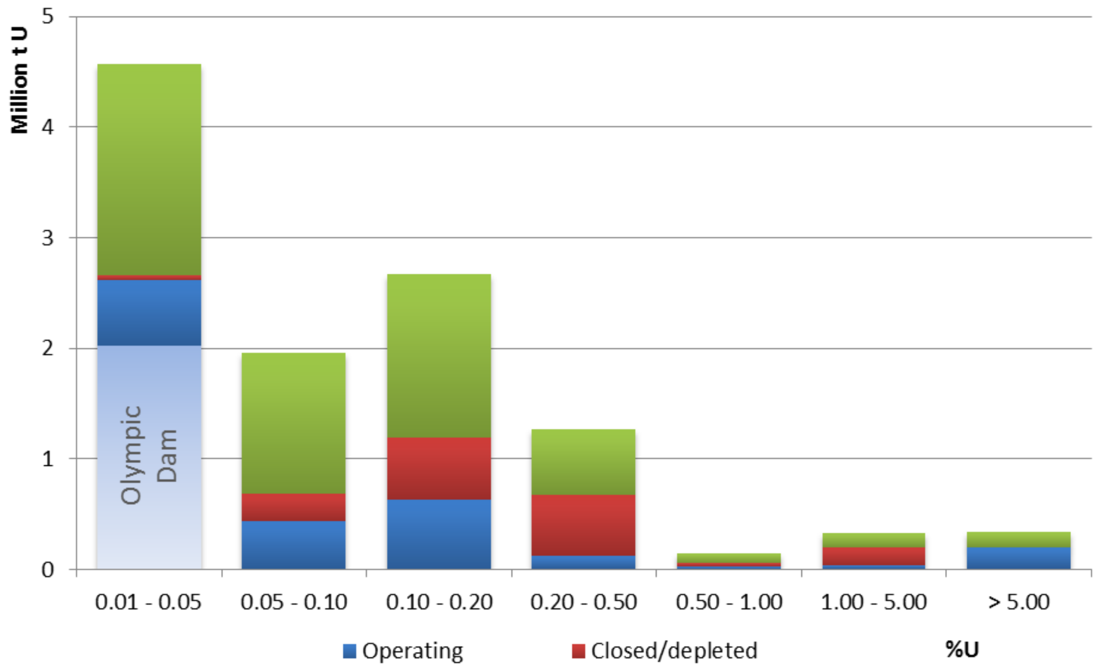

FIGURE 23: GRADES OF URANIUMDEPOSITS BASED ON 1270 DEPOSITS[20] FROM UDEPO 2010 (IAEA, 2012)

The last figure of this subchapter shows the average grade of mines evaluated in project. For most countries the grades are around 0.1 %. The exceptions are Canada with a very high average of 10% and Namibia at an average of only 0.028%. The numbers include operating and proposed/planned mines.

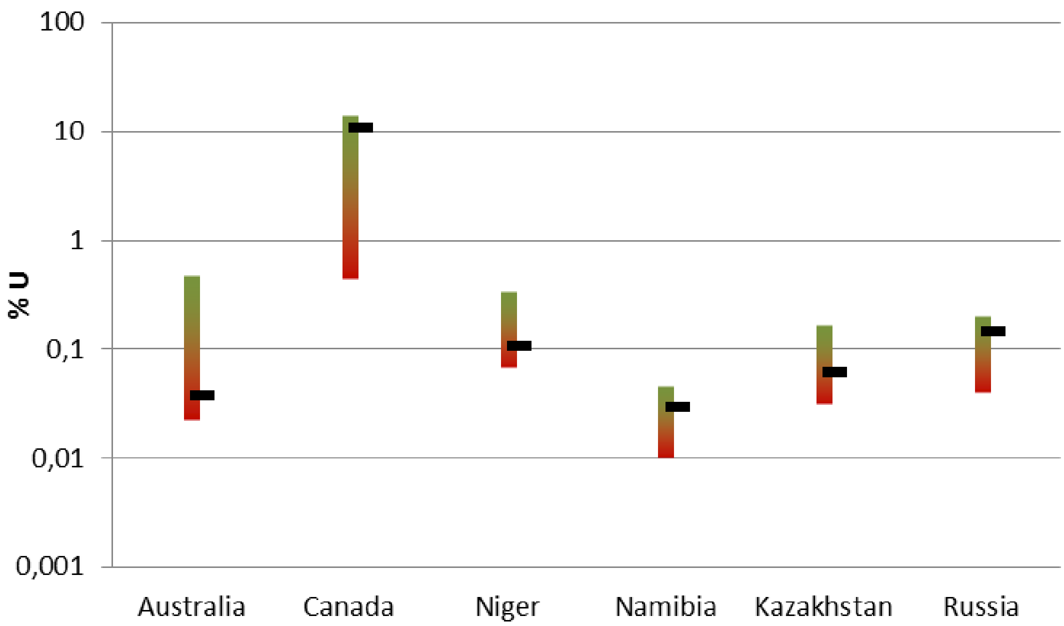

FIGURE 24: GRADES OF OPERATING AND PLANNED MINES BY COUNTRY

[20] No unconventional resources included.

2.2.4 SOCIOECONOMIC ASPECTS AND ENVIRONMENTAL IMPACTS

Once a deposit was discovered, the resources defined and technical and economic aspects were considered feasible, it does not mean that the uranium mining can be conducted. Legal, political and social factors are essential for a mining operation.

The legal framework is established by the national authorities. The operator must obtain an operating license[21] and fulfill regulations concerning environmental protection, worker health and safety as well as public health. While this is necessary for every mining operation, additionally radiation protection and enhance security aspects have to be considered for uranium mining. These requirements differ from country to country and may be time and cost intensive. These regulations have to be reviewed and renewed after some time or if changes in the operation are planned. Uranium production thus relies a lot on these frame conditions. In Saskatchewan, as an example, life time and capacity extension for existing facilities didn't seem possible as no new tailings facilities were licensed[22]. About two years ago the situation seemed to have changed as the mining company Areva prepared an environmental assessment for an expansion project at the McClean Lake tailings management facility. In mid-2012 the requirements for environmental assessments changed and the environmental assessment for such projects are now no longer required (WISE, 2013b). Thus, there were three different legal situations within only a few years.

The influence of politics and the communities can be exemplified by Canada and Australia. The most recent event occurred in Quebec, Canada where the environmental minister announced a temporary moratorium on uranium exploration and mining end of March 2013 (Kilkenny, 2013). The opposite occurred in Western Australia, where uranium mining was banned from 2002 to 2008 although there are some promising deposits present. In 2008, with a change in the government the ban was lifted (WAtoday, 2008). The first mine since then was approved in early 2013 (Wiluna) and is scheduled to start operation within the next two year (ABC News, 2013). One important aspect in Australia is the attitude of the indigenous population, as they often own the land rights in relevant areas and thus have to be involved in mining decisions.

In addition the environmental aspects and legacies of uranium mining shall be mentioned. Especially in the past, uranium mining was performed regardless of the consequences. Areas where mining was carried out now require decades of expensive care[23] to restore the ecological initial state[24].

Finally, the handling of fissile material is always related to proliferation risks. This shall be only stated at this point, as a comprehensive discussion is not part of this workpackage.

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[21] A license is also necessary for exploration work, as mentioned above.

[22] Personal information at IAEA technical meeting.

[23] Cameco estimated its decommissioning and reclamation costs for the Saskatchewan operations at 260 million $ in 2009.

[24] Further information on uranium legacies can be found at www.wise-uranium.org/indexu.htm. An upcoming publication on "managing environmental and health impacts of uranium mining" by the OECD/NEA targets to discuss current and past mining practices and respective regulations.

2.2.5 GEOGRAPHIC DISTRIBUTION AND SECURITY OF SUPPLY

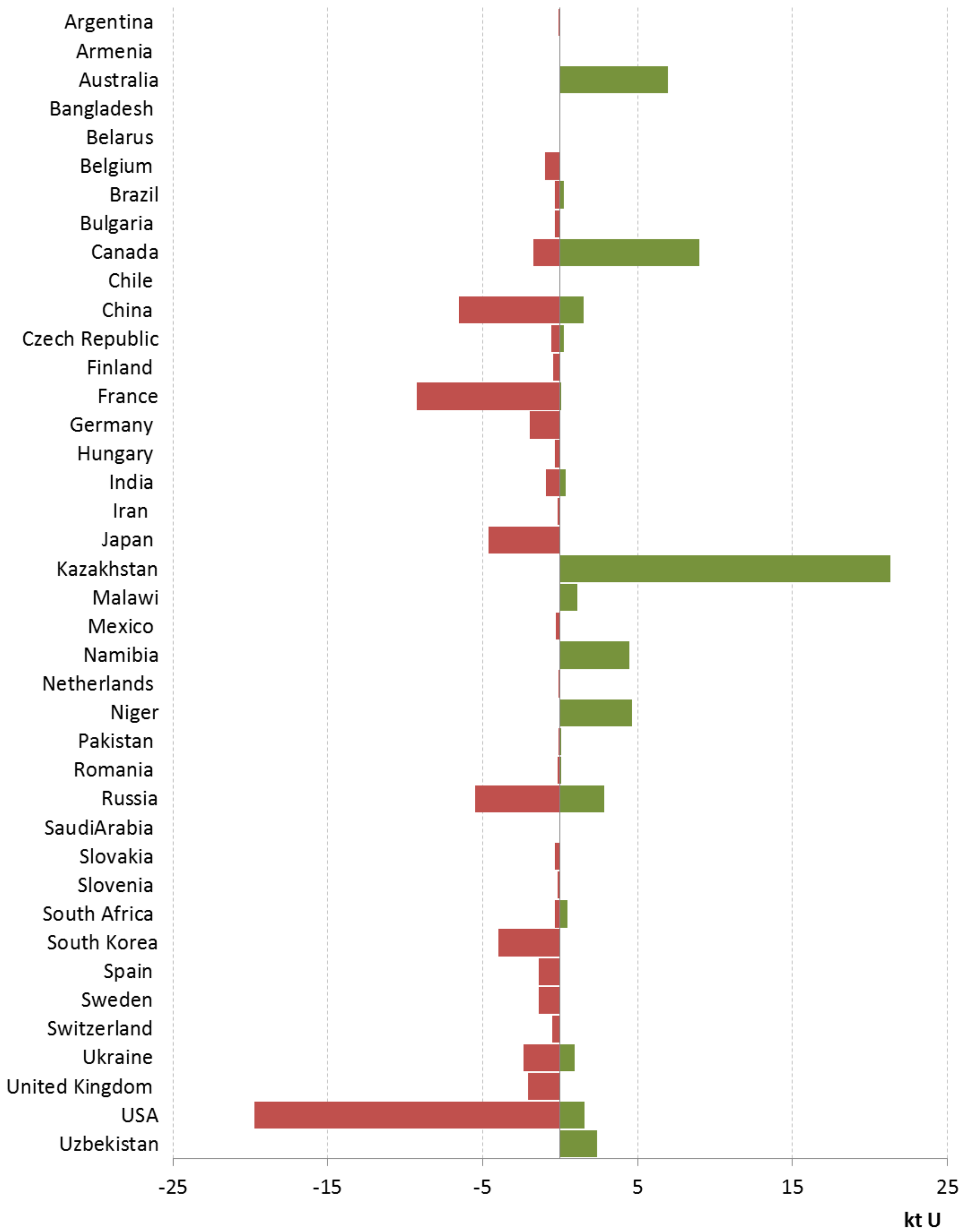

FIGURE 25: URANIUM PRODUCERS AND CONSUMERS

A characteristic point of the global uranium supply is the geographical imbalance of producers and consumers. Only two countries that operate nuclear power plants meet their uranium requirements from own production. This leads to two relevant aspects: The necessity of transportation of nuclear material and the aspects of security of supply.

Concerning transportation of yellowcake (UOC)[25] it can be stated, that it has a good safety record, compared to the amount of shipments. Nonetheless, especially with an increasing nuclear and more transports, can course not be precluded. Strict regulations and implementation of accident management plans are thus necessary and have to be applied over the whole nuclear fuel cycle network (Figure 26).

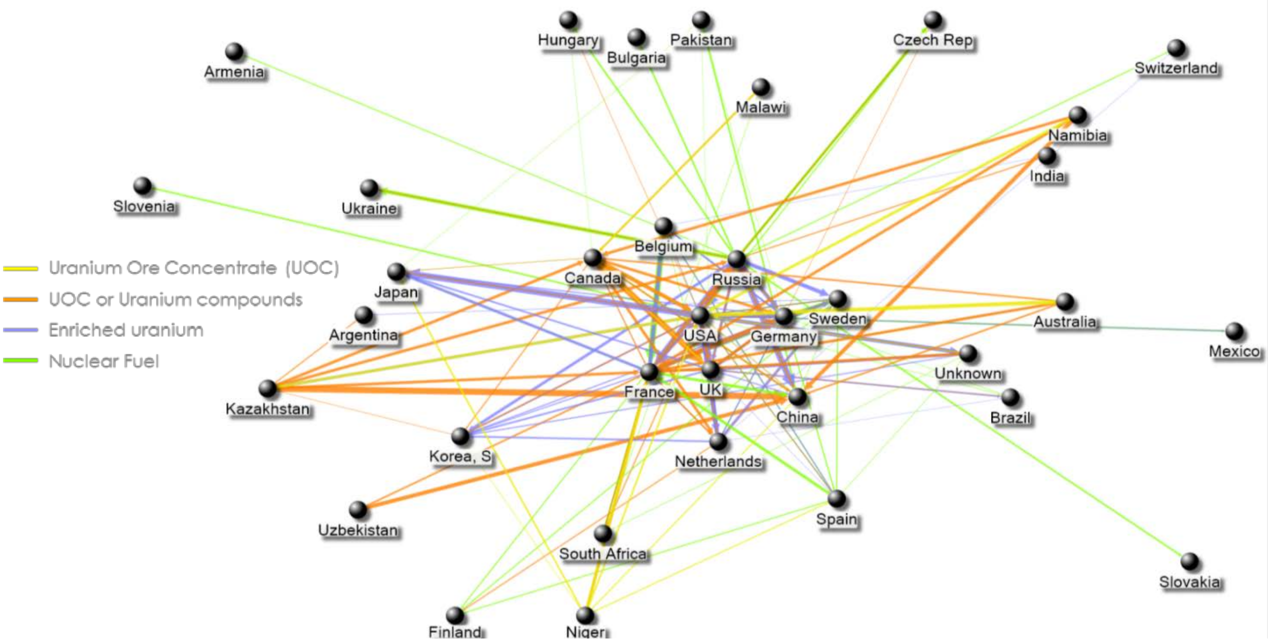

FIGURE 26: THE FUEL CYCLE NETWORK

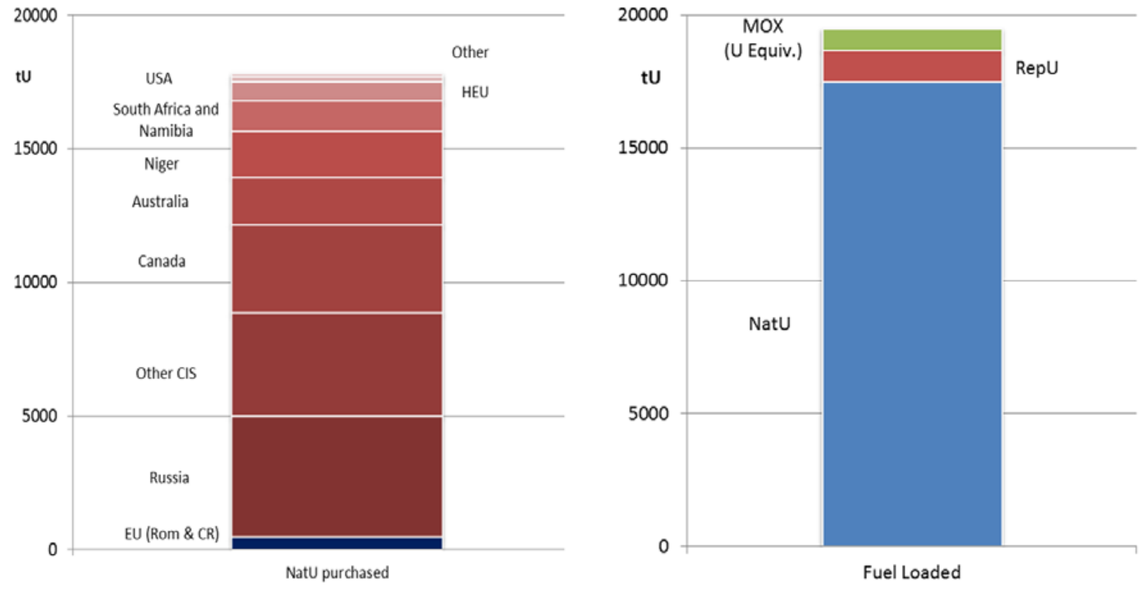

FIGURE 27: URANIUM BOUGHT BY EU AND FUEL LOADED BY EU FACILITIES IN 2011 SOURCE: (EUROPEAN COMMISSION, 2012)

25 Uranium Ore Concentrate (UOC) has a rather low specific activity. Health concerns arise mainly due to its chemical toxicity as a heavy metal.

The European Union is a region heavily dependent on Uranium imports (Figure 27). In 2012 the EU could only cover 2.5% of its uranium demand by domestic production. About half of the EU fuel is imported from CIS states; a quarter of the uranium and a third of the enrichment work is purchased directly from Russia. This stands somewhat in contrast to promoting nuclear energy as aspect to gain independence from Russia in terms of energy feedstock.

In order to deal with such security of supply related issues the European Supply Agency was established within the Euratom Treaty. The buildup of stocks is seen as one of the main measures to address security of supply issues (European Commission, 2012):

"The Euratom Supply Agency also recommends that EU utilities maintain an adequate level of strategic inventories and use market opportunities to increase their stocks, depending on their individual circumstances. The aggregate stock level at the end of 2011 totaled 47 343 tU, which could fuel EU utilities' nuclear power reactors, on average, for at least two and a half years."

The issue of dependence on foreign uranium was already broached in the 2011 publication "Nuclear Energy in Europe: Uranium Flow Modeling and Fuel Cycle Scenario Trade-Offs from a Sustainability Perspective" (Tendall and Binder, 2011). The authors modeled the European fuel cycle compare their different fuel scenarios from an environmental, economic, and social perspective. They conclude:

"….Our results suggest that nuclear energy involves several tradeoffs. The technological and investment choices depend on the priorities set at the national or even European level. From a geopolitical perspective, the import of raw material (Europe requires about 24,000 t/y natural uranium, of which 95% is imported), with a high dependency on countries such as Russia (providing 25% of uranium and 31% of enrichment services) would imply that if Europe continues with nuclear energy (which currently produces 30% of European electricity,2 SI Figure S1), it should focus on further development of new technologies (e.g., fast reactor systems), which require less raw materials and are able to recycle waste materials. However, increasing material efficiency is not correlated with the reduction of other impacts. Indeed if such a measure is taken, proliferation risks for example are highly uncertain and expected to increase. Furthermore, the European nuclear fuel cycle causes significant externalities which cannot be ignored: more than half of depleted uranium produced is disposed of outside the system; slightly less than half of the natural uranium is processed outside the system, causing accumulation of wastes, and emissions outside the European borders……"

2.3 UNCONVENTIONAL URANIUM

The first exploration wave for uranium started fifty to sixty years ago when nuclear weapons entered the focus of US politics. The second exploration wave followed in the early phase of nuclear energy research between 1960 and 1980 when the fast expansion of nuclear reactor technology and huge demand for uranium was expected.

Already at that time it became evident that uranium resources probably are not able to feed the uranium requirement for a long lasting expansion of nuclear reactors. Therefore, already at that time unconventional ways to extent uranium supplies were investigated.

Possible uranium extraction from sea water, for the first time, was investigated in the 1960ies and 1970ies. The technology to extract uranium from sea water was analyzed as being feasible, at least in principle.

A third possible path way was seen in the concept of breeding of spent fuel with the concept of nuclear breeding reactors. Soon it became obvious, that, from a technical perspective the breeding concept by far was the most realistic option. Therefore research on nuclear breeding reactors was prioritized in the 1970ies.

2.3.1 URANIUM FROM PHOSPHATES

Phosphate ores also contain impurities. The most important ingredient beside phosphate is uranium. For the phosphate producers, the uranium content is a burden, as it reduces the quality of phosphate and its use as fertilizer.

For instance, German phosphate fertilizer in average contains 283 mg uranium per kg of P_2O_5 with up to 1,713 mg per kg of P_2O_5 (BW, 2012). Typical fertilizer output of 22 kg phosphate per hectar results in the uranium uptake of the soil of between 10 to22 g uranium per hectare and year (BRD, 2012). The Red Book (OECD-NEA / IAEA, 2012, p. 31) summarizes various resource estimates. The most important countries are listed in Table 3.

TABLE 3: UNCONVENTIONAL URANIUM RESOURCES FROM PHOSPHATE ROCKS SOURCE: (BRD, 2009; OECD-NEA / IAEA, 2012)

	Uranium resources (1000 tU)	Uranium content in phosphate rock (ppm)
Morocco	6526	100-130
Mexico	240	30
Brazil (included in RAR)	76	800
Jordan	60	20-70
Peru	21.6	60
Egypt	35-100	50-200
South Africa		430

Uranium production from phosphate rocks was commercialized in the U.S. Between 1954 and 1972 a total of 17,150 tU was recovered in Florida with production focus on military needs. A second wave during 1970s to 1990s was largely for civil nuclear reactors with a production rate of about 1,000 tU/yr. However, the production ceased due to diminishing phosphate production from domestic mines and due to the drop of the uranium price. The U.S. phosphate industry has passed peak production around 1980 (see Figure 28). In parallel to the declining phosphate production in the U.S., producers more and more had to develop lower grade ores. Moroccan phosphate rock between

1975 and 1999 was processed in Belgium with a cumulative production of 686 tU. Up to 40,000 tU were recovered during before 1990 from marine organic deposits in Kazakhstan (OECD-NEA / IAEA, 2012, p. 32).

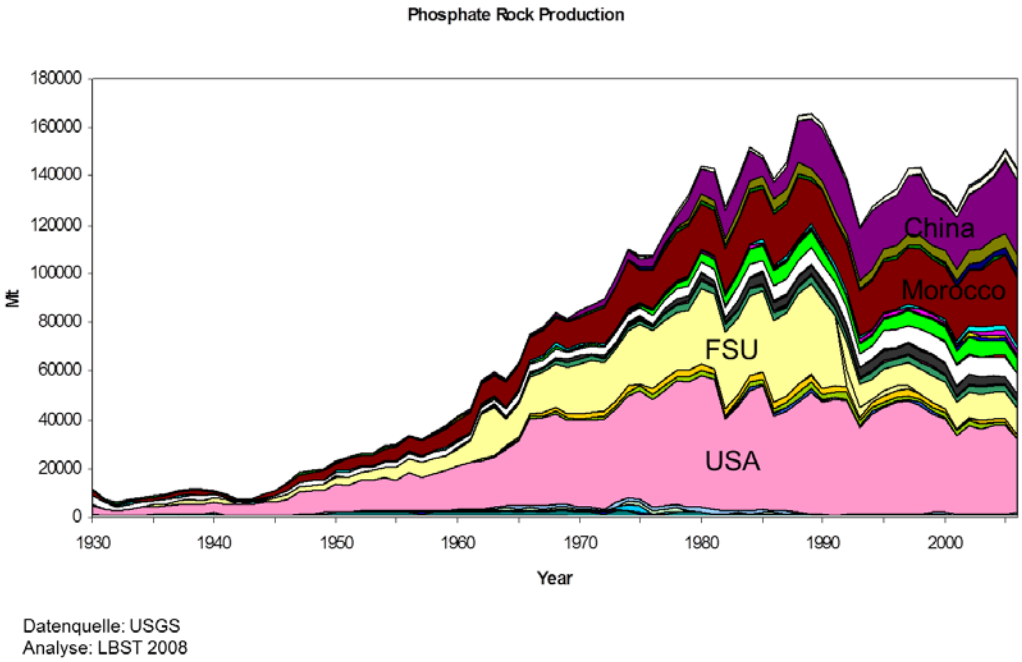

FIGURE 28: WORLD PRODUCTION OF PHOSPHATE ORE (USGS, 2009)

In the past, uranium was produced by solvent extraction from phosphoric acid plants. It is estimated that at existing phosphoric acid production centers at maximum about 11,000 tU/yr could be produced (OECD-NEA / IAEA, 2012, p. 33)

In addition, “Cameco and Uranium Equities Ltd are setting up a demonstration plant in the USA using a new refined process – PhosEnergy – and estimate that worldwide some 7,700 tU could be recovered annually as by-product from phosphate production” (WNA, 2013e).

At present, two projects are under construction in Brazil, Santa Quiteria and Itataia mines. These have reserves of 340 Mt of phosphate containing 140,000 tU at Santa Quiteria and 80,000 tU at Itataia. The uranium content in P_2O_5 amounts to about 0.054%.The plant capacities are 1,270 tU/yr from about 2015 in Santa Quiteria and 970 tU from Itataia (WNA, 2013e).

The renaissance of the discussion of phosphate deposits as a source of uranium supplies also must be seen in the context that the phosphate ores with diminishing uranium content are more and more depleted and producers have to touch more uranium rich mines. But also the limited primary uranium resources give a strong incentive for the search of new production capacities.

The uranium content in phosphate ores varies between 8 to 220 mg per kg phosphate (BRD, 2009). A rough calculation taking care of average uranium content in different phosphate deposits results in a total uranium resource of about 22 million tons which might be contained in phosphate reserves.

However, as phosphate ore grades decline, so do uranium contents, even when the relative share of uranium to phosphor remains constant. However, the uranium ore grade is still far too low to allow commercial primary production of uranium. Therefore, an estimate of the possible future production rate is based on phosphate production rates. This limits the possible contribution of uranium from phosphate resources. An estimate of possible production rates based on phosphate production results in a possible contribution of uranium supply from phosphate production in the range of 11,000 t/year (OECD-NEA / IAEA, 2012, p. 33).

2.3.2 URANIUM FROM SEAWATER

2.3.2.1 HISTORICAL RESEARCH AND EXPERIMENTS

One concept focused on the separation of uranium from sea water via a titanium oxide filter (Williams and Gillam, 1978). Uranium does not adsorb on the titanium oxide but accumulates in front of the filter not being able to penetrate through its mesh size. The corresponding technical concept was to construct a fixed filter with an accumulating trough in front of it to collect uranium oxide. The sea water should be pumped through the filter.

A fast plausibility calculation exhibits the enormous pumping effort required which would result in a very low energy return on energy invested: The uranium content of sea water with 3 ppb in average would require the throughput of at least 333 million kg in order to extract 1 kg of uranium. The lifting of 333 million kg water up to 5m height would require 1.6 $*10^{10}$ J energy[26] just for water pumping, if all energy and material losses are neglected. For comparison: the typical annual consumption of 180 t uranium per 1 GW_e reactor breaks down to the specific energy output of $1.6 \cdot 10^{11}$ J (electricity) per kg of uranium input. Therefore, even when 70% pumping efficiency and 50% filter efficiency are assumed the energy return on energy invested declines to three. In other words: the uranium extraction consumes at least one third of the technical energy which can be produced from the extracted uranium. Not yet included are additional energy losses for the power plant and uranium life cycle such as energy for construction and demolition of plants as well as energy for fuel recycling and disposal.

A second independent concept was developed to avoid the huge energy requirement for water pumping. The idea is to fabricate ropes which can adsorb uranium at their surface. These ropes should be put into natural streams of ocean water. The natural flow would help to collect the uranium like a grid. The energy requirement would be focused on the fabrication and preparation of the grids, on their purging and recycling and on the final extraction of the uranium from the purging fluids.

Early work was also performed in Germany: The KFA Jülich investigated cultures of algae and naturally occurring Schwarztorf as adsorbents and ways to extract the uranium from the water (Heide et al., 1973). This work finally resulted in several patent applications (Heitkamp and Wagner, 1987; Paschke et al., 1981).

[26] : $E = M*g*h = 333*10^6$ kg*9.81 m/s² *5 m; with E=Energy, M=mass, g= gravitation constant, h=height.

Experimentally, uranium extraction from sea water was predominantly investigated in Japan. Early Japanese work was already published in 1969 (Ogata and Kakihana, 1969). The investigations focused on the influence of ions and adsorbents to accelerate or delay the uranium uptake (Tabushi et al., 1979; Yamashita et al., 1980).

Apart from recent US experiments the most reasonable results are published by Japanese researchers. About ten years ago these performed large scale experiments which resulted in the extraction of 1 kg uranium from seawater over 240 active days of adsorption. These experiments are described in the following.

2.3.2.2 DESCRIPTION OF JAPANESE EXPERIMENTS 1999 - 2004

A 6,000 m² large and 13 micrometer thick polypropylene foil with poly ethylene surface was activated by the following treatment process to enhance uranium adsorption:

The foil was radiated for 2 hours 40 minutes with an electron beam of 200 kGy. The radiated foil was dipped in dimethyl sulfur oxide with acrylonitrile and acryl acid. This was followed by chemical treatment of the surface molecules (cyan groups) with hydroxylamine transforming them into amidoxime to enhance their reactivity (Seko et al., 2003). The electron beam photography in Figure 29 shows the change of surface structure and sketches the various steps of chemical activation of the foil.

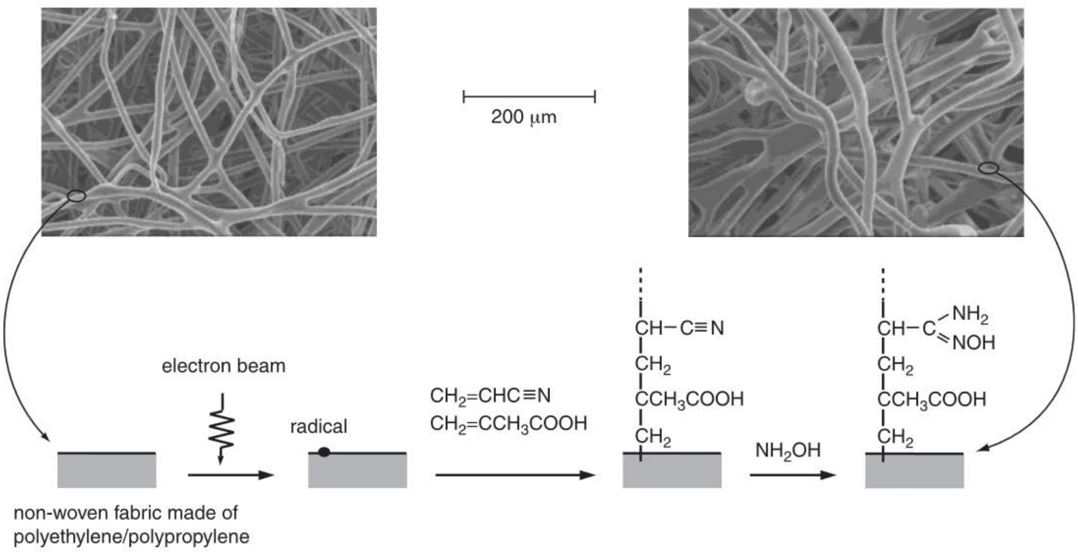

FIGURE 29: ACTIVATION OF POLYETHYLENE/POLYPROPYLENE FOIL BY ELECTRON BEAM RADIATION AND SUCCEEDING BATH IN ACRYLONITRILE AND ACRYL ACID. IN A THIRD STEP (RIGHT) CYAN GROUPS ARE TRANSFORMED WITH HYDROXYLAMINE IN AMIDOXIME GROUPS. FOILS TREATED IN SUCH A WAY EXHIBITED HIGHEST ACTIVITY FOR URANIUM ADSORPTION (SEKO ET AL., 2003).

Next the meanwhile 0.2 mm thick foils are cut in 29 x 16 cm² sheets. Each package of 120 sheets is clustered by means of spacers into individual stacks. Each 144 stacks (12 times 12) are bundled to cubes. Each four cubes form an adsorption cage. These steps are illustrated in Figure 30:

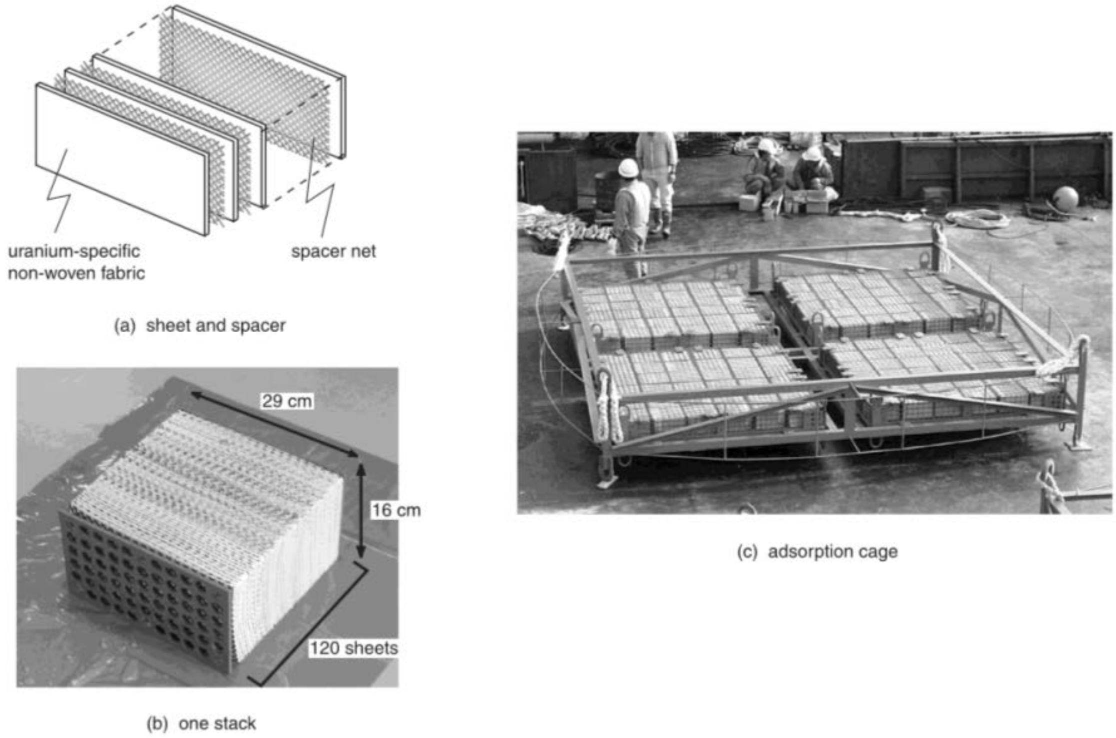

FIGURE 30: BUNDLING OF 120 FOILS WITH SPACERS (TOP LEFT) INTO STACKS OF 19 CM X 26 CM SIZE (BOTTOM LEFT); FOUR CAGES OF 144 STACKS ARE SHIFTED INTO A COMMON METAL FRAME (RIGHT). (SEKO ET AL., 2003)

Three metal frames are bundled and fixed at the ground of the sea as shown in Figure 31.

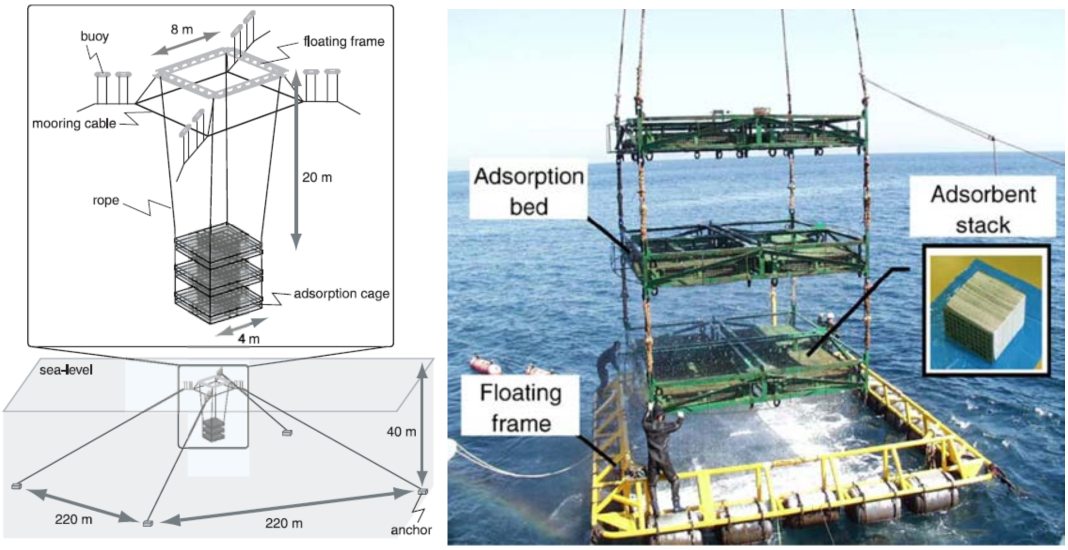

FIGURE 31: URANIUM FROM SEAWATER. LEFT: GEOMETRIC SKETCH OF THE SYSTEM WITH THREE LAYERS OF 4 X 144 STACKS CONTAINING 120 FOIL STRIPES. RIGHT: PHOTOGRAPHY OF THE INSET OF THE APPARATUS IN THE FRAME. LEFT GRAFIC (SEKO ET AL., 2003), RIGHT FOTO (TAMADA ET AL., 2004).

Within the three years period between 1999 and 2001 twelve experiments were performed. After each 20 to 100 days the stacks were removed and several times bathed in hydrochloride acid to remove the adsorbed metals. Then the stacks were purged in potassium hydroxide solution and reactivated for the next experiment. The removed metals were chemically treated to extract alkali and earth alkali metals. Over 240 active days of adsorption a total of 1,083 g of uranium are extracted from sea water.

2.3.2.3 ANALYSIS OF JAPANESE EXPERIMENTS AND EXTRAPOLATIONS

The Analysis of the paper of Seko et al. (2003) exhibits that a typical adsorption rate of 0.011 – 0.027 g per day was achieved per stack with 810g weight. This transforms into an average adsorption rate of about 0.013 – 0.03 g/kg/day of adsorption foil. After 100 days of adsorption this would result in an uptake of 1.3 – 3 g-U/kg.

The overall analysis exhibits that for the extraction of 1,083 g uranium about 350 kg of plastic foils and several tons of stabilizing frame structure were needed. In average once per month the foils were removed for uranium extraction and purged for recycling. This process needed bathing in 1 percent hydrochloride acid (for the removal of alkali metals) and 50 percent hydrochloride acid. Finally, the foils were purged for recycling in potassium hydroxide solution. The assumption that about 700 kg acids and solutions are needed for the extraction of 1 kg uranium gives a rough estimate of material throughput.

A typical 1 GW_e reactor needs about 180 t uranium fuel per year to produce 8 TWh_e of electricity. Therefore, the annual fuelling of one reactor requires 63,000 t of adsorption foils, probably more than 200,000 tons of steel frames and more than 100,000 tons of hydrochloride acid and potassium hydroxide.

A rough calculation by counting the energy demand for steel production with 15 kWh/kg and for plastic foils with 7 kWh/kg results in more in about 0.5-0.7 TWh of energy demand for the process, when a life time of 20 years is assumed for the steel construction. Not yet included is the effort for the circulation of the chemicals (pumping), their recycling and mechanical work for the many repeating processes as well as the effort for the plant construction. Compared to the TiO2 filter method this would increase the energy return on energy invested to about 10.

If one day the world uranium demand of 67 kt/yr was to be supplied by uranium from seawater, the above described production method would require 23 million tons of plastic foils, about 70 million tons of steel and at least 50 – 100 million tons of HCl and KOH. This would require about 40 percent of present world plastic production and by far more than the world production of hydrochloride acid and potassium hydroxide solution.

From today's perspective it is highly unrealistic to feed one day many nuclear reactors with uranium from seawater extracted with this method. This might only be possible with a highly improved technical concept avoiding mass and energy efforts. The preparation of the foils must be simplified and the adsorption rate must be enhanced considerably.

2.3.2.4 IMPROVED JAPANESE EXPERIMENTS AND COST EXTRAPOLATION

Indeed, Tamada et al. performed improved experiments with new geometric braid adsorbents reducing the recovery effort considerably. For such a system some cost calculations are performed. These adsorbents showed an enhanced uranium uptake of 1.5 g/kg after 30 days at 30°C compared to the old stacks with about 0.5 g/kg uranium uptake at about 20°C(see Figure 32).

Figure 33 gives the results of the cost scaling of the Japanese experiments according to Tamada (2006). Under the assumption that an improved absorbent with 2g uranium uptake per kg adsorbent could be found and recycled for six times, the total cost would amount to 88,000 Yen/kgU.

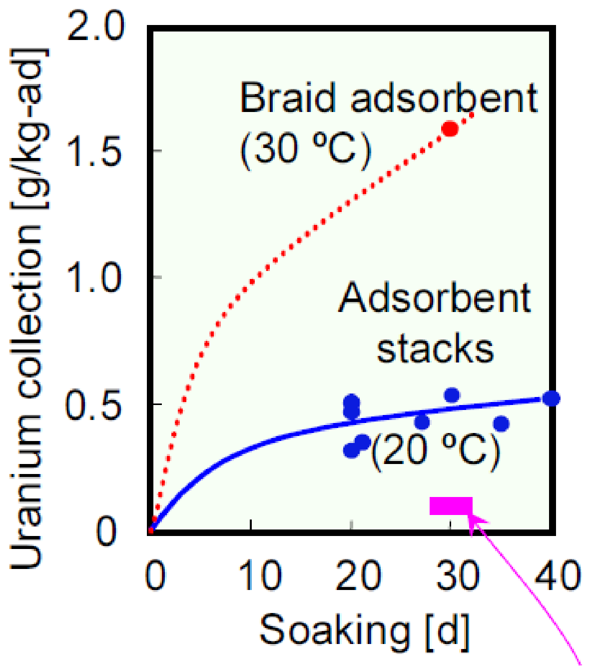

FIGURE 32: URANIUM UPTAKE OF BRAID ADSORBENT IN RELATION TO THE URANIUM UPTAKE BY ADSORPTION FOILS(TAMADA, 2006)

This might further reduce to about 25,000 Yen per kg uranium when a 4 gU/kg adsorbent could be used with 18 repetition uses. Here it should be kept in mind that the present experiments with 1.5 gU/kg uptake would increase the present cost to about 117,000 Yen/kgU when 6 repetitions are possible before the braids damage. The conversion with 100 Yen = 1.3 US$ results in the price of 900 $/kg at 1.5 gU/kg.

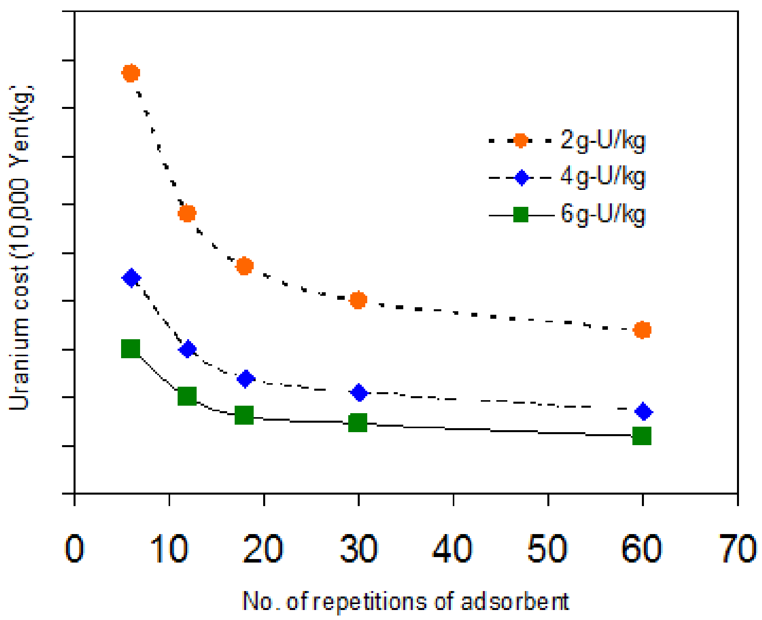

FIGURE 33: COST SCALING OF URANIUM PRODUCED FROM SEAWATER IN RELATION TO THE RECYCLABILITY OF THE ADSORPTION FOILS ACCORDING TO THEORETICAL CALCULATIONS (TAMADA, 2006)

2.3.2.5 RECENT RESEARCH IN THE USA AND COST CALCULATIONS

The USA started a research program with the aim to improve the economics and mass balance of the system by new materials and technologies (Griffith, 2012).

First results come from experiments performed by ORNL-researchers which so far have achieved the highest uranium uptake (ORNL, 2012). The adsorption capacity of their material HiCap was up to 3.94 g uranium per kg of adsorbent or 0.4 percent. The adsorbent had a surface area about ten times larger as the materials used by Tamada (2004) and Seko (2003). It seems that also the recyclability is higher. Adsorption tests in a saltwater solution containing 6 ppm uranium (sea water has about 3 ppb uranium content) resulted in a maximum uranium uptake of 146 g per kg of adsorbent or 14.6 percent.

A core constituent of the new material is the replacement of poly-acrylamidoxime used in the Japanese experiments by more environmental benign materials. A major candidate material seems to be chitin extracted from shrimp shells (BBC, 2012).

Schneider et al. (2012) performed economic calculations on the life cycle cost as well as energy balance calculations of the braid adsorbent system as developed by Tamada (2006).

The basic assumption for their cost calculations are:

- Annual uranium production: 1,200 t/yr
- Adsorption capacity of braid system: 2 g U/kg adsorbent
- Length of mooring campaign: 60 days
- No. of adsorbent uses (recycling): 6 times
- Adsorbent degradation per cycle: 5%
- Interest rate of capital: 10%
- Amortization period of buildings: 30 years
- Amortization period of equipment: 15 years

Based on these assumptions uranium cost of 1230 USD/kgU are calculated. The cost share of individual components is given in Figure 34. By far the largest cost share comes from the adsorbent production, predominantly hydroxylamine in Methanol/water. Half that share comes from capital as well as operating cost of the mooring of the braids.

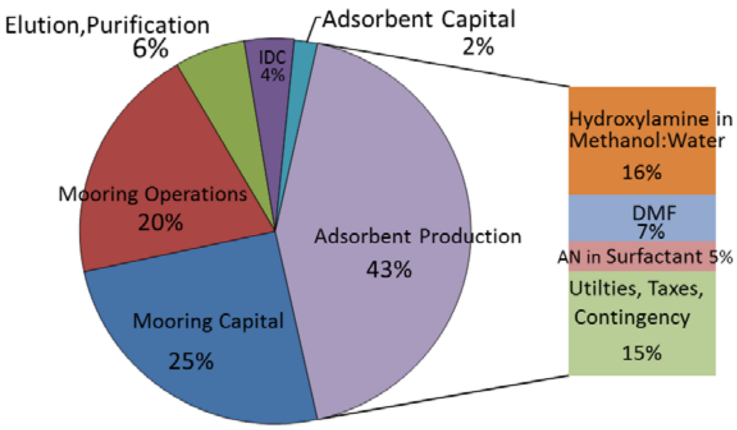

FIGURE 34: COST COMPONENTS OF URANIUM-FROM-SEAWATER EXTRACTION PLANT AS CALCULATED BY SCHNEIDER (2012)

Figure 35 gives a parameter variation of uranium uptake and recyclability of the material. Cost rise sharply with declining material stability below 3 to 4 recycling cycles. Minimum costs are achieved with about 10 cycles. Further recycling increases the cost again due to the degradation of the braids (5% adsorption reduction at each recycling is assumed). Based on the figure it seems that a material which could adsorb at least 6 g U/kg adsorbent would result in minimum cost around US $ 350-500/kg U if more than 4 cycles can be achieved.

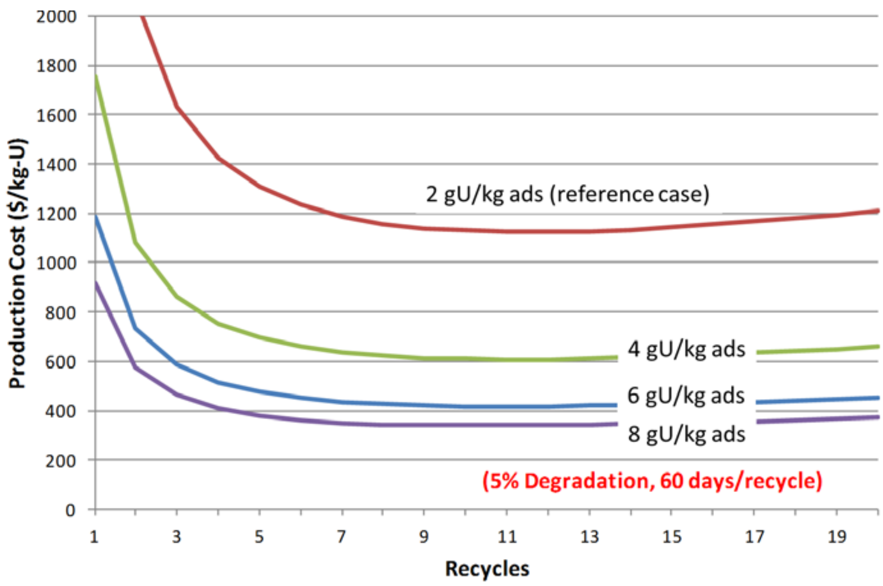

FIGURE 35: URANIUM EXTRACTION COST FROM SEAWATER BASED ON DIFFERENT ASSUMPTIONS ON URANIUM ADSORPTION CAPACITY AND RECYCLABILITY OF THE ADSORBENT (SCHNEIDER ET AL., 2012)

Figure 36 gives the cost of selected parameter calculations based the above method. A reference price between 100 – 335 USD/kgU for uranium at spot market between 2006 – 2001 is given. A possible system based on present state-of-art technology might result in uranium supply cost of about 1230 USD/kgU. This might be reduced by advanced materials in the range 450 – 660 USD/kgU. Even ideal materials with 18 recycling uses, no degradation of adsorption and 6 gU /kg adsorbent uptake would require uranium cost above 330 USD/kgU.

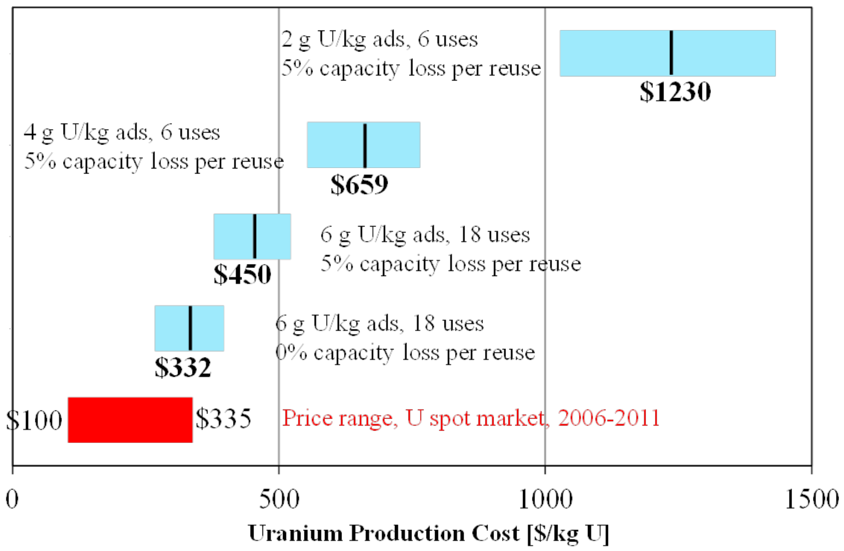

FIGURE 36: COMPONENT COST AS A RESULT OF NUMBER OF RECYCLES (SCHNEIDER ET AL., 2012)

2.3.2.6 ENERGY RETURN ON ENERGY INVESTED (EROEI) AND MASS BALANCE

Schneider (2012) also calculated the energy requirement for such a system more detailed than the rough estimates above.

Figure 37 gives the results of these calculations for the reference case (2g U/kg ads; 5% degradation per cycle; 5 cycles). The total energy requirement sums up to 24,000 MJ/kg. Compared to the electricity production from uranium (1.6 * 10^{11} J; see above) this results in an EROEI of 16/2.4 = 6.7.

Schneider 2012 calculate the EROEI = 22. This is based on the assumption that spent fuel will be reprocessed in reprocessing plants, adding additional energy output. However, at present state of the art reprocessing of the fuel is only restricted to a small portion of spent fuel. And this will likely remain so in the foreseeable future due to capacity restrictions.

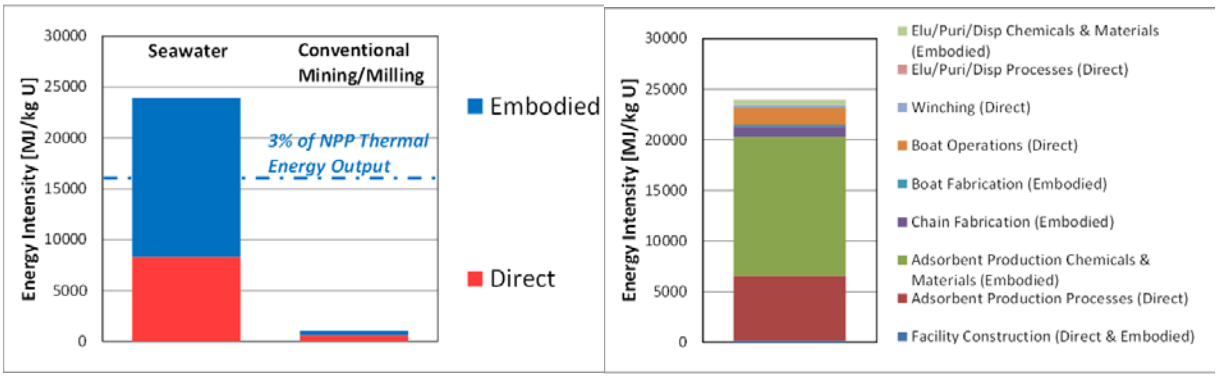

FIGURE 37: ENERGY REQUIREMENT FOR THE EXTRACTION OF 1 KG URANIUM FROM SEAWATER WITH THE REFERENCE BRAID MATERIAL (2 GU/KG ADSORBENT; 6 USES; 5% DEGRADATION PER USE) (SCHNEIDER ET AL., 2012)

Though the energy balance still seems to be positive the huge mass of adsorbent needed results in another bottleneck. For instance, the supply of 180 t/yr of uranium to feed one nuclear reactor would require the mass of 180,000 kg U/(0,002 kg ads/U) = 90,000t of adsorbent, resp. 15,000 tons adsorbent if 6 reuses are practicable.

The production of 10% of world uranium demand requires about 6,000 t uranium resp. 500.000 tons of adsorbent if the uranium had to be extracted from seawater.

Further research predominantly concentrates at the Bhaba Atomic Research Center in India and China (Linfeng, 2011).

2.4 SECONDARY SOURCES OF URANIUM

In 2010 worldwide uranium production covered about 85% of demand (OECD-NEA / IAEA, 2012, pp. 60, 76). The remaining 9,205 t U had to be covered by so called “secondary sources”. Surplus production in former years offers the largest secondary supply source. However, this potential is limited. At best, the gap between demand and supply can be closed as long as stocks from historical production surplus are exhausted. This would require a complete conversion of military arsenals which is unrealistic.

At year end 2010 this difference amounted to about 560,000 t (OECD-NEA / IAEA, 2012, p. 104). Already consumed uranium for military purposes, research reactors and small scale nuclear applications probably have reduced it by 250,000 – 350,000 t (own estimate). Thus an annual contribution up to 10,000 t/year at best could be supplied from stocks for about 20-30 remaining years. Actually much will depend on at which extent and how fast highly enriched uranium from arms conversion can be converted and used for civil nuclear reactors.

To a small extent the reprocessing of burned uranium can be made useful in form of mixed oxide elements (MOX) and reprocessed uranium (RepU). However, corresponding capacities are small (up to 5 kt/yr), the effort is huge and only a small number of reactors are adapted to its use. In face of long lead times, huge invest costs and strong resistance it cannot be assumed that this situation might change considerably within the next 10 – 20 years.

In 2013 the bilateral Russian-US contracts for uranium from arms conversion ceases. Actually the Russian side has not given signs to a prolongation this contract. This will considerably reduce the supply capacity from arms conversion.

The potential to supply uranium from secondary sources will be discussed in this chapter. Figure 38 gives an overview of the uranium supply situation in 2012. The supply from primary production is taken from (WNA, 2013a). The secondary supply is estimated from 2010 data. In the following some basic aspects of uranium enrichment and depletion are discussed as these determine the dynamics of uranium production from secondary sources considerably.

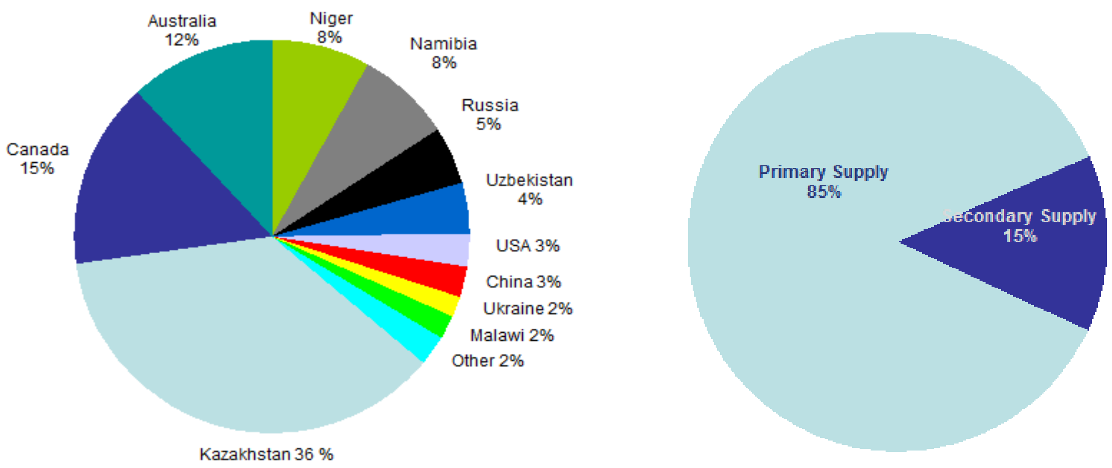

FIGURE 38: PRIMARY (LEFT) AND SECONDARY (RIGHT) URANIUM SUPPLY IN 2012

2.4.1 INTRODUCTION: GENERAL ASPECTS OF URANIUM ENRICHMENT AND DEPLETION

The reactor relevant uranium isotope ^{235}U has a share of 0,711% in natural uranium. Most active reactors are pressurized water (PWR) or boiling water reactors (BWR) which require the fuel enrichment of ^{235}U to 3-5%. Correspondingly enriched uranium is called low enriched uranium (LEU). Uranium used for weapons must be enriched at least to 85%, but typically to more than 90% of ^{235}U. Uranium with a ^{235}U content of more than 20% is called high enriched uranium (HEU). Heavy water reactors and graphite moderated reactors on the other hand can be operated with natural uranium with ^{235}U content of 0.711%. Their fuel must not be artificially enriched.

The backside of uranium enrichment is the large amount of depleted uranium in the tailings. Usually, during the enrichment process the remaining stock is depleted to less than 0.3% of ^{235}U. This depleted uranium is added to stocks and used for certain applications. For instance, due to its high gravimetric density it is used as balancing mass in aircraft wings or in racing yards. Also in the military context it is used to enhance potential effects of conventional weapons in so-called uranium mantled munitions.

Today, about 5% of depleted uranium is used for above mentioned purposes. Further amounts are stored and used for HEU-depletion in the context of arms conversion or for other dilution purposes of highly enriched uranium. The highly enriched uranium is blended with depleted uranium in such a ratio that the resulting blend can be used in typical commercial nuclear reactors.

From time to time the discussion heats up whether depleted uranium from stockpiles should be depleted further by concentrating the ^{235}U in a small share to commercial fuel type uranium. The following Figure 39 gives an imagination of the size of this potential fuel source.

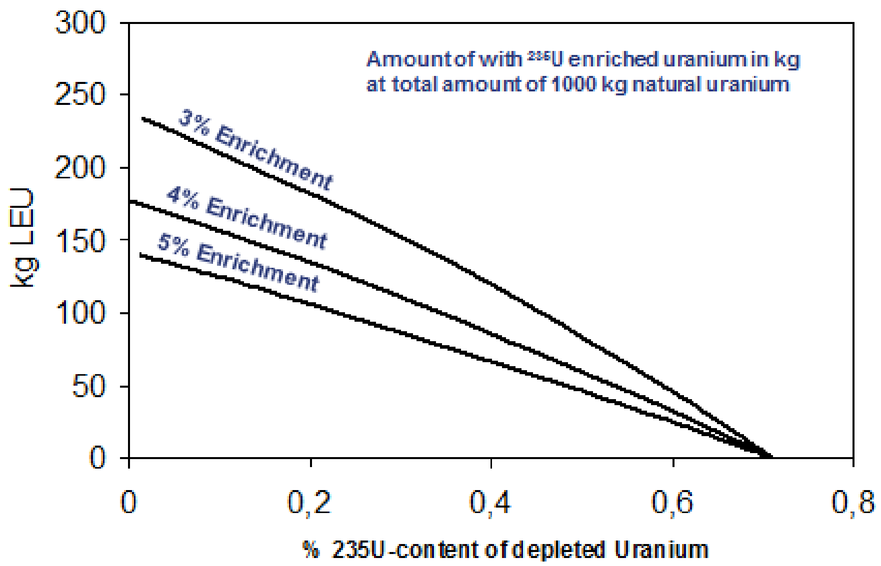

FIGURE 39: URANIUM ENRICHMENT. THEORETICALLY, FROM 1000 KG NATURAL URANIUM AN AMOUNT OF 233 KG OF 3% ENRICHED URANIUM CAN BE EXTRACTED WHILE THE REMAINING STOCK IS DEPLETED TO 0% OF ^{235}U CONTENT. THE FIGURE SHOWS HOW MUCH LEU CAN BE PRODUCED DEPENDING ON THE DEPLETION OF THE REMAINING URANIUM STOCK. THE SUM OF DEPLETED AND ENRICHED URANIUM IN THIS EXAMPLE ALWAYS ADDS TO 1000 KG.

From the amount of 1000 kg natural uranium (0.711% share of ^{235}U) between 87 kg (enriched LEU with 5% 236U) and 150 kg (enriched LEU with 3% 236U) of enriched uranium can be extracted by depleting the rest mass to 0.3%. Further depletion of the remaining 850 913 kg from 0.3% to 0.2% adds another 30 kg (LEU at 3%) to 19 kg (LEU 5%).

Similarly, the enrichment to HEU depletes the stocks much faster as Figure 40 exhibits. The production of 4.7 kg HEU (85%) from 1000 kg natural uranium results in 995.3 kg uranium depleted to 0.3% 235U content. Further depletion to 0.2% could add another 1.2 kg HEU. The total depletion of the rest mass would result in the maximum amount of 8 kg HEU.

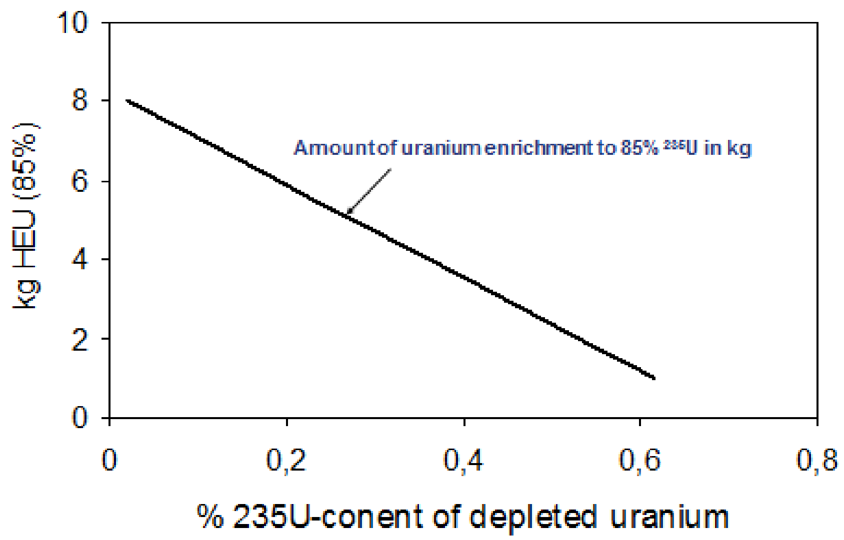

FIGURE 40: HEU ERNICHMENT. FROM 1000 KG NATURAL URANIUM 8 KG HEU (85%) COULD BE PRODUCED BY EXTRACTING ALL ^{235}U FROM THE REMAINING MASS. THE FIGURE EXHIBITS HOW URANIUM CAN BE ENRICHED IN DEPENDENCE OF THE URANIUM CONTENT OF THE DEPLETED URANIUM. THE SUM OF ENRICHED AND DEPLETED URANIUM CORRESPONDS TO 1000 KG.

Vice versa, highly enriched uranium can be diluted by blending with depleted uranium to use it in nuclear power plants.

One kg of HEU (90% 235U) corresponds to 130 kg natural uranium (0.711% 235U). The thinning of HEU to nuclear fuel can be performed by blending with 1.5% enriched 235U or with depleted uranium (0.3% 235U). The dilution of 1 kg HEU (90% 235U) to LEU (4.4% 235U) corresponds to 280 – 290 kg natural uranium (0.711 % 235U).

However the energetic effort of blending steeply rises with the desired level of dilution. This energetic effort is described with the separative work unit (SWU). It can be calculated by the following formula:

$W_{SWU} = P*V(x_p) + T*V(x_t) + F*V(x_f)$

with

P	product
T	tail
F	feed
x_p	^{235}U content of product
x_t	^{235}U content of tailing (depleted uranium stock)
x_f	^{235}U content of feed stock

and

$V(x) = (1-2x)*ln(1/x - 1)$

$F/P = (x_p-x_t)/(x_f-x_t)$

$T/P = (x_p-x_f)/(x_f-x_t)$

Figure 41 illustrates these relations. For instance, the energetic effort to produce 1 kg LEU (5%) from natural uranium (0.711%) by depletion to 0.15% is about twice the effort for its production by depletion to 0.3% from a correspondingly larger amount of natural uranium. This is also illustrated in Figure 41.

Figure 42 gives a quantitative example of the energetic effort and remaining stock of depleted uranium.

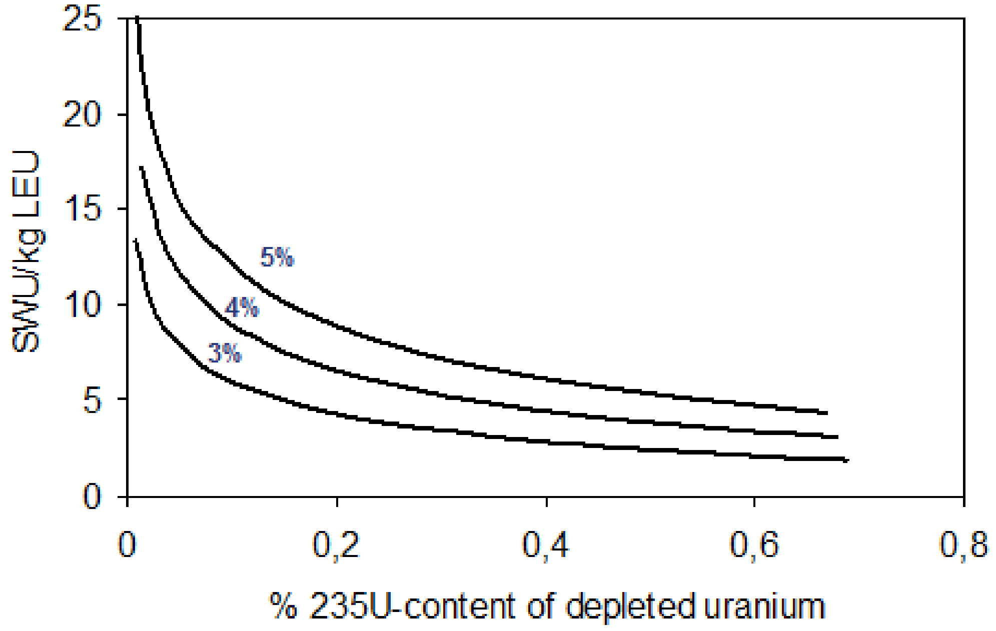

FIGURE 41: SEPARATIVE WORK UNIT (SWU) FOR THE PRODUCTION OF ENRICHED URANIUM BY THE DEPLETION OF NATURAL URANIUM. THE DIFFERENT CURVES GIVE THE EFFORT FOR THE ENRICHMENT TO 3, 4, OR 5 % ^{235}U. THE DEPLETION OF THE TAILING TO LESS THAN 0.1% ^{235}U REQUIRES AN OVERPROPORTIONAL HIGH EFFORT.

From these considerations it becomes obvious that the degree of depletion is determined by energetic and economic conditions. If the cumulative mined uranium of 2,590 kt of natural uranium equivalent in average was used to produce to 4% enriched uranium while depleting the total stock to 0.3%, about 85 percent of the mined natural uranium is still included in the depleted stocks. However depleting that further to 0.2% would only add 250 kt or 10%, though the technical and economic effort would rise tremendously.

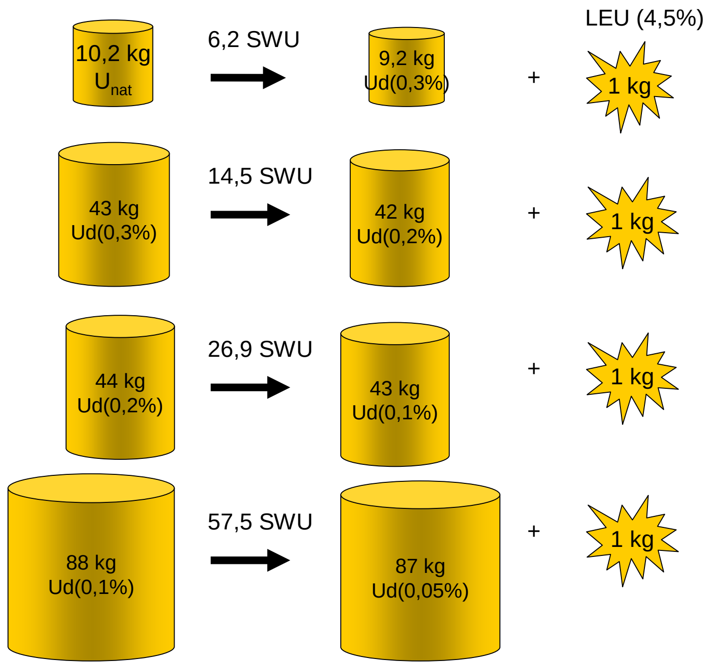

FIGURE 42: SEPARATION EFFORT AND REQUIRED AMOUNT OF URANIUM TO PRODUCE 1 KG LEU WITH 4.5% ^{235}U. THE EFFORT RISES IN DEPENDENCE OF THE FEEDSTOCK-CONCENTRATION AND THE CONCENTRATION IN THE TAIL.

2.4.2 THE DEPLETION OF HIGHLY ENRICHED URANIUM (HEU)

The USA and Russia produced more than 95% from worldwide HEU (90 – 95% ^{235}U) for nuclear weapons. The remaining 5% are produced by France, UK, and China and to a very small amount by other nuclear states (IAEA, 2001b).

Since the end of the cold war various national and international nuclear disarmament agreements are set into force to convert military HEU to LEU which then could be used in nuclear reactors or was disposed due to its low quality. In the following the most known conversion programs between Russia and USA as well as national conversion programs inside USA are covered and quantified as far as possible.

2.4.2.1 BILATERAL CONTRACTS FOR THE CONVERSION OF HIGHLY ENRICHED URANIUM FROM MILITARY USES

Under the slogan „megatons to megawatts“ Russia and the USA undersigned a bilateral agreement in 1993 with the content to convert 20,000 Russian nuclear weapons with 500 tons HEU (90% ^{235}U) over the period of 20 years to nuclear fuel to be used in commercial reactors in the USA (NTI, 1993).

The conversion program is organized and led by the two organizations TENEX (Tekhsnabeksport – an export company under the authority of the Russian Department for external affairs) and U.S. Department of Energy (DoE). The DoE concentrates the activities under the newly founded and 1998 privatized U.S. Enrichment Corporation (USEC). A total price of 12 billion US Dollar was negotiated for the delivery of 15.260 t LEU (~4.4% ^{235}U) resulting from the depletion of 500 t HEU to the U.S. Part of this agreement was the buildup of a national uranium reserve up to 22,000 t natural uranium equivalent in form of UF_6 at each side. According to the contract this reserve could only be brought to the market from 2009 onwards.

In 1996 an addendum to the contract was added which regulated prices and deliveries in detail (NTI, 1999). An additional commercial contract was established in March 1999. According to that contract between 1999 and 2013 about 9,100 t natural uranium equivalent should be delivered annually from the outstanding 138,000 t. Of that amount up to 6,700 tons natural uranium equivalent should be sold and delivered directly from Russia to the companies COGEMA; Cameco Group and NUKEM Inc. The remaining 2,500 tons natural uranium equivalent per year should be sold predominantly to the USA. Only in case of a low demand of the contract partners the quantities were allowed to be stored and stockpiled (IAEA, 2001b).

The following Table 4 summarizes the deliveries of blended HEU from Russian military sources to the U.S. between 1995 and 2013. Since the deliveries from Russia to the USEC are already blended to LEU (4.4% ^{235}U) as UF_6 the low deliveries from 1997 on could be due to different reasons:

It is possible that original military warheads contained HEU with lower quality below 90% ^{235}U, or the blending with other uranium was lower than 1.5% ^{235}U enriched. In both cases lower total amounts of uranium are needed to convert the same tonnage amount of 500 t HEU.

Until 24th May 2013 in total 19,008 nuclear warheads with 475.2 t HEU were converted and 13,723 t LEU (4,4 %) were delivered to the USA via USEC (USEC, 2013).

As early as 2003/2004 the interest grew in the USA to prolong the contract beyond 2013 and to contract further amounts of converted Russian HEU for use in US nuclear power plants (NTI, 2004). However, at 5th June 2006, the head of TENEX, Vadim Mikerin, announced that the Russian government had no interest to prolongate the contract beyond the year 2013 (Mikerin, 2006). This statement still holds today (OECD-NEA / IAEA, 2012, p. 107).

Instead of prolonging this contract, a new “Transition Supply Contract” was established in December 2011. Its content is “to purchase about 21 million separative work units (SWU) through 2022 with a mutual option to purchase up to another 25 million SWU during that period. The low enriched uranium supplied by TENEX will come from Russia’s commercial enrichment activities rather than from down blending of excess Russian highly enriched uranium.” (USEC, 2013).

TABLE 4: DELIVERIES OF CONVERTED URANIUM FROM RUSSIA TO USEC BETWEEN 1995 AND 2013. FIRST COLUMN GIVES THE YEAR; IN 1995 THE FIRST SHIPMENT WAS SETTLED. THE SECOND COLUMN GIVES THE NUMBER OF WITHDRAWN WARHEADS, THE THIRD COLUMN THE HEU CONTENT OF THESE WARHEADS. EACH WARHEAD CONTAINED 25 KG HEU. COLUMN „T LEU (THEO.)"GIVES THE DELIVERED URANIUM AS CALCULATED ON THE ASSUMPTION THAT 25 KG HEU (90% ^{235}U) PER WARHEAD WAS BLENDED WITH 1.5% ^{235}U ENRICHED URANIUM TO A BLEND WITH 4.4% ^{235}U. COLUMN "T LEU (REAL)" GIVES DELIVERIES AS REPORTED BY USEC. COLUMN "T UEQ (0.711%)" GIVES THE AMOUNT OF NATURAL URANIUM WHICH CORRESPONDS TO THE DELIVERED QUANTITIES. THIS IS BASED ON THE ASSUMPTION THAT LEU AT 4.4% WOULD BE BLENDED WITH 0.3% DEPLETED URANIUM TO GET NATURAL URANIUM EQUIVALENT AT 0.711%. THE SEPARATIVE WORK UNITS NEEDED FOR THIS PROCESS ARE GIVEN IN THE COLUMN "SWU". DATA FOR 2012 AND 2013 ARE ADAPTED TO BALANCE CUMULATIVE TOTALS. (USEC, 2009) AND OWN CALCULATIONS.

Year	**No of war heads**	tHEU	tLEU (theo)*	tLEU (real)	t Ueq (0,711%)	**SWU**
1995	244	6.1	186	186	1,860	1,121
1996	479	12	366	370.9	3,709	2,235
1997	534	13.4	409	358.5	3,585	2,160
1998	764	19.1	583	571.5	5,715	3,444
1999	970	24.3	742	718.7	7,187	4,331
2000	1,462	36.6	1,117	1,037.8	10,378	6,254
2001	1,201	30	916	904.2	9,042	5,449
2002	1,201	30	916	879	8,790	5,297
2003	1,203	30.1	919	906	9,060	9,060
2004	1,202	30.1	919	891	8,910	5,369
2005	1,206	30.1	919	846	8,460	5,098
2006	1,207	30.2	922	870	8,700	5,243
2007	1,212	30.3	925	840	8,400	5,062
2008	1,204	30.1	919	834	8,340	5,026
2009	1,204	30.1	919	834	8,340	5,026
2010	1,204	30.1	919	834	8,340	5,026
2011	1,204	30.1	919	834	8,340	5,026
2012	1,152	28.8	879			
2013	1,147	28.5	870			
Total	**20,000**	**500**	**15,258**	**12,716**	**127,156**	**80,227**

Exact numbers on total HEU amounts are not available, however, it is estimated that the 500 t HEU converted under the existing contract are less than half of the total HEU being produced in Russia in former times. The estimate holds that Russia could convert at least another 350 t HEU from warheads to burn it in nuclear power plants (NTI, 2009).

On 30 September 2008 the Domenici Amendment to the 1993 contract was enacted into law, allowing the Russian Federation access to 20% of the post-2013 U.S. uranium nuclear fuel market, on the condition that the Russian Federation completes the down blending of an additional 500 t HEU under the terms of the existing HEU purchase agreement. It also allowed the post-2013 access to 25% of US market, on the condition of further down blending of 300 t HEU (OECD-NEA / IAEA, 2012, p. 108).

Though these numbers seem to be huge it must be kept in mind that this is an optional HEU-conversion program offered by US government while the Russian Federation government already had denied to renew the existing 1993 agreement. The total numbers of US and Russian HEU quantities covered by these and the following US down blending programs probably exceed the total military uranium stocks.

2.4.2.2 U.S. PROGRAMS TO THE CONVERSION OF HIGHLY ENRICHED URANIUM FROM ATOMIC WEAPONS

The above shown quantities from Russia are marketed in the USA. Further conversion agreements are under force to make available additional military HEU quantities from U.S. stocks for civil nuclear reactors. These are summarized in this subchapter.

Among other aspects the U.S. Energy Policy Act of 1992 (EPACT) requires a balancing of uranium stocks stored in the U.S. A similar directive was also requested for the depletion of HEU-stocks and its use in civil reactors (EPACT, 1992). Parallel to the above sketched Russian-American HEU conversion program the USA government obliged itself to reduce considerable HEU amounts from its nuclear arsenal.

In July 1996 the U.S. Government removed 174.3 t HEU from warheads (USEC, 2009), of which 151 t HEU should be blended and made available for commercial nuclear reactors. The remaining 23 t HEU should be diluted further and disposed (OECD-NEA / IAEA, 2006b, p. 65). At end 2005 a total of 72.9 t HEU were blended to 894.7 t LEU (OECD-NEA / IAEA, 2006b, p. 65), at end 2007 a total of 89 t HEU were converted to nuclear fuel (Agostino et al., 2008). In contrast to Russian HEU these warheads had been enriched to less than 90% ^{235}U. Therefore the corresponding LEU amount was much less: The 89 t HEU corresponded to 1,282 t LEU or to a natural uranium equivalent of 12,820 t (under the assumption that LEU (4.4%) would be produced from natural uranium by depletion to 0.3% ^{235}U (own calculations)).

In addition, contracts between DoE (Department of Energy) and TVA (Tennessee Valley Authority) in 2001, 2004, and 2008 allocated a total of 44.6 t HEU to be converted to BLEU (blended LEU with a small share of ^{236}U) in the frame of an agreement between Department of Energy and TVA and to be used between 2003 and 2007 in the TVA research reactor. In May 2011 another agreement between DoE and TVA allocated further 28 t HEU for downblending in order to meet TVA reactor fuel needs through 2022 (OECD-NEA / IAEA, 2012, p. 108).

The above agreements removed a total of 246.9 t HEU from warheads while delivering 1,282 t LEU or 12,820 t natural uranium equivalents to commercial reactors. The rest was either down blended and disposed or used for ships and research reactors not entering commercial markets.

The DoE announced in September 2005 the conversion of another 200 t HEU from military stocks. From these quantities only 20 t corresponding to about 2,850 t natural uranium equivalent (own calculation) will be made available within a 25 years period for commercial reactors. The remaining amount will be used for the propulsion of the nuclear ship Savannah (160 t HEU) and for research reactors and space applications (20 t HEU) (OECD-NEA / IAEA, 2012, 2006a, p. 108).

Also in 2005 DoE announced to set aside another 17.4 t HEU for downblending and to LEU fuel and reserve stock for commercial reactors in case of market disruptions (OECD-NEA / IAEA, 2012, p. 108). In August 2011 a reserve of 230 t LEU was reached within this agreement, sufficient for the reload of six reactors of 1 GW_e size. The total downblending will add another 60 t LEU (corresponding to ~ 600 t natural uranium equivalent) until end 2012. These will be sold on the market to pay for the downblending and processing cost (OECD-NEA / IAEA, 2012, p. 108).

Finally, in December 2008 another 67.6 t HEU were declared unallocated in the DoE's Excess Uranium Inventory Management Plan (DOE, 2008). This material will become available for disposal over several decades.

Partly the published details of HEU conversion to LEU and its commercial use in nuclear reactors are confusing and highly intransparent. Though many numbers are published it is by no means obvious which quantities already have been converted and are delivered annually. Therefore the below given totals are an own estimate based on available literature.

Within the 1993 conversion agreement between Russia and USA 12,440 t natural uranium equivalent are still available in terms of UF_6 which are already delivered but are not allowed to be converted before 2009 (DOE, 2008).

As the optionally agreed conversion of another 800 t of Russian HEU is highly uncertain, at the end of the Russian-US agreement the annual availability of uranium from arms conversion probably will reduce from about 10,000 t to 2,000-3000 t natural uranium equivalent.

TABLE 5: DECOMMISSIONED MILITARY HEU STOCKS WHICH ARE MADE AVAILABLE FOR CIVIL REACTORS AND FOR DISPOSAL

Year of agreement	**HEU conversion**	Origin	Still available at end 2011	Conversion potential for civil reactors at end 2011
1993	500 t	Russia	57.3 t HEU	14,572 t U_{eq}
2008	500 t (optionally)	Russia	Beyond 2013	130,000 t U_{eq}
2008	+ 300t (optionally)		Beyond 2013	78,000 t U_{eq}
1996	174.3 t, herof 151 t for reactors 23 t for disposal	USA		
2001	33 t (downblended to BLEU)	USA		0
2004	+ 6 t (downblended to BLEU)	USA		0
2008	+ 5.6 t (downblended to BLEU)	USA	21.8	0

Year of agreement	HEU conversion	Origin	Still available at end 2011	Conversion potential for civil reactors at end 2011
2011	+28 t (downblending to BLEU)	USA	28	0
2005	200 t, (160t for ship; 20t research; 20t for commercial reactors)	USA	180 (?)	5,000 t U_{eq}
2005	17.4 t (downblending as reserve for commercial reactors)	USA	3 (?)	4,000 t U_{eq}
2008	67.6 t for disposal	USA	67.6	0
Total	1831.9 t HEU (corresponding to 465,000 t natural uranium equivalent)		1158 t HEU (opt) 358 t HEU	231,000 t U_{eq} (opt.) (23,000 t U_{eq}

TABLE 6: ORIGINAL AND AT END 2010 STILL AVAILABLE AMOUNTS OF MILITARY HEU STOCKS. THE ORIGINAL TABLE WITH BASE YEAR 2003 (CISAC, 2005) IS BACKWARD CALCULATED AND SUPPLEMENTED WITH ORIGINAL AMOUNTS FOR 1995 AND FORWARD CALCULATED TO END 2010 DATA. THESE CALCULATIONS ARE ONLY PERFORMED FOR USA AND RUSSIA. THE TERM "EXCESS" INCLUDES THOSE QUANTITIES WHICH ARE ALREADY REMOVED FROM MILITARY STOCKS BUT NOT YET NECESSARILY CONVERTED TO REACTOR FUEL.

Country	Military HEU 1995	Of which Excess	At end 2010 already converted	Remaining Excess at end 2010	Total remaining military HEU at end 2010
Belgium	--				--
China	20+- 5				20+- 5
France	30 +-7				30 +-7
Germany					
India	?				?
Israel	--				--
Japan	--				--
North Korea	?				?
Pakistan	1-1,25				1-1,25
South Africa					
UK	~21				~21
US	750 +-50	532	231 (?)	301	519+-50
Russia	1270+-300	500 (+800?)	442.7	57.3 (857?)	827+-300
Total	**2090+-360**	**874**	**674**	**430**	**1418+-360**

2.4.3 CONVERSION OF PLUTONIUM AND REPU FROM REPROCESSING PLANTS

2.4.3.1 CONVERSION OF PLUTONIUM FROM NUCLEAR WEAPONS

Another potential fuel source is the disposal of military and civil plutonium stocks. In June 2000 Russia and USA signed an agreement to remove at least 34 t of warhead feasible plutonium from its military stocks at each side from 2007 onwards. The Russian government announced to use all this plutonium in civil nuclear reactors while USA claimed to dispose 8.5 t. The remaining 25.5 t should be used in MOX-fuel rods and burned in civil reactors. For this purpose new MOX fabrication plants should be built in both countries. The conversion rate should amount at least 2 t Pu/year, but should be extended to at least 4 t Pu/year by the help of already existing conversion plants in other states (USR, 2000).

The conversion procedure was modified several times in later agreements. At present, Russia should have started between 2010 and 2012 while the construction of the MOX fabrication plant in USA is in delay (WNN, 2013) . The US MOX fabrication plant will be built and at Savannah River and was expected to produce commercial quantities in 2016, but now is delayed until 2019, at earliest (OECD-NEA / IAEA, 2012; WNN, 2013). The total of 68 t Plutonium corresponds to 14,000 to 16,000 t natural uranium equivalent and 4,760,000 SWU based on the assumption that the conversion of 1 t plutonium corresponds to 205 t of natural uranium and 80,000 SWU. The conversion rate of 4 t Pu/year will correspond to 480 t/year of natural uranium which would become available over a 17 years period.

TABLE 7: QUANTITIES OF PLUTONIUM AVAILABLE AT END 2003 (CISAC, 2005)

Country	Military Pu 2003	Of which Excess	At end 2010 already converted	Pu from civil reactors
Belgium	--			3.5
China	4.8±2			0
France	5±1.5			78
Germany	--			11
India	0.3-0.47			2-3
Israel	0.5-0.65			
Japan	--			5.4
North Korea	0.015-0.038			
Pakistan	0.02-0.06			
South Africa				
UK	7.6	4.4		96
US	85	38	0	14.5
Russia	145±25	50	0	38
Total	**248±30**	**92**	**0**	**~250**

CISAC (2005) and Diehl (2006) assume, that at world level about 250 t plutonium in warhead quality existed at end 2003. Out of these, 92 t were seen as “excess plutonium” and could become available for arms conversion. The above discussed conversion of 2 x 32 t = 68 t plutonium are part of that „excess plutonium“.

Plutonium is also produced in conventional civil nuclear reactors at normal operation. It is estimated that at end 2003 worldwide about 250 t plutonium are separated from burned uranium fuel of civil nuclear reactors in reprocessing plants, predominantly in France and UK (see Table 4 2). This amount has changed slightly until end 2013.

The ^{235}U contained in fuel rods is not fully converted into fission products. A part of the not fissioned fuel content ^{238}U is converted into plutonium during operation (see Figure 43).

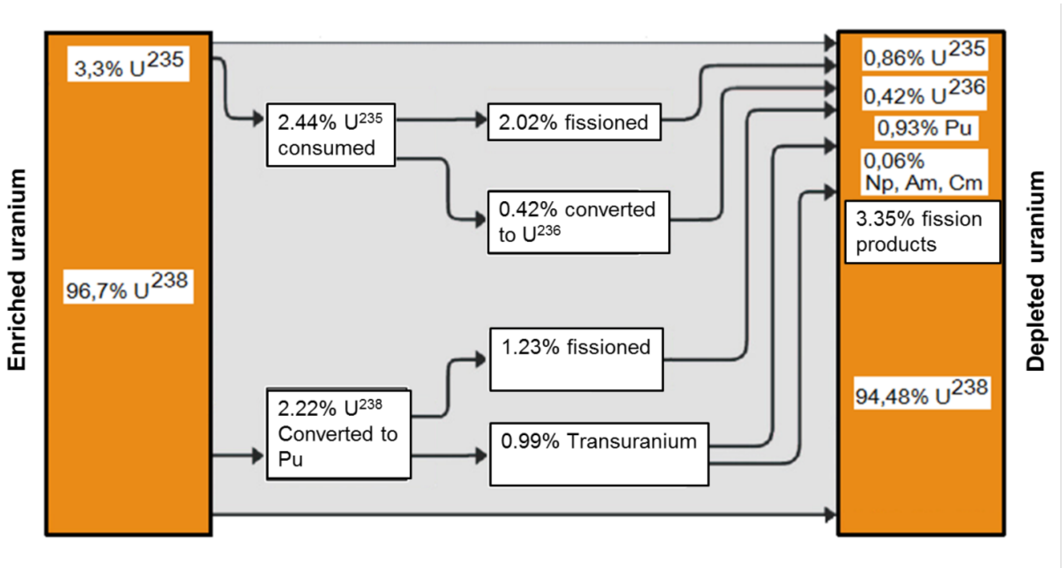

FIGURE 43: COMPOSITION OF NUCLEAR FUEL BEFORE AND AFTER BURNING IN NUCLEAR REACTORS (WEIDNER, 2009)

Burned fuel rods contain 0.86% ^{235}U and 0.93% plutonium isotopes (^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu). About two thirds of the produced plutonium mass are fissionable ^{239}Pu and ^{241}Pu (Wikipedia, 2013b).

The fission of ^{235}U produces 200 MeV of heat per reaction. The fission of ^{239}Pu produces a similar amount of heat per reaction (Finkelnburg, 1967). The separation of fissionable plutonium isotopes from burned nuclear fuel increases the energy content of the fuel by about 21 percent. The separation of the plutonium and of the still fissionable ^{235}U increases the energy content by about 22 percent. This calculation is based on a light water reactor with a burning rate of 45,000MWd per t LEU (4% ^{235}U) (Wikipedia, 2013b)

The reprocessing of burned fuel rods is performed predominantly in La Hague (France) and Sellafield (UK). In 2008 France processed 937 t of burned fuel rods (Areva, 2009). Japan constructed a reprocessing plant which was expected to start operation in 2009. However after many problems and the Fukushima disaster these plans are stopped. It was planned to process 800 t burned fuel rods per year which was 80% of the total burned rods in Japan (JNFL, 2013).

TABLE 8: REPROCESSING PLANTS IN OPERATION 2008 (ENS, 2013)

City	State	Capacity [tU/yr]	Start of operation
La Hague	France	UP 2: 1000 UP 3: 1000	1994 1990
Sellafield	UK	Magnox: 1,500 THORP: 900	1964 1997
Trombay	India	60	1965
Tarapur	India	100	1982
Kalpakkam	India	100	1998
Rokkasho	Japan	800	2009 ?
Tscheljabinsk	Russia	400	1978
Krasnoyarsk	Russia	800	?
Total		**6,460**	

FIGURE 44: REPROCESSING PLANT SELLAFIELD, UK (LEDINGHAM, 2009)

FIGURE 45: REPROCESSING PLANT LA HAGUE, FRANCE (AREVA, 2009)

Various reprocessing methods use solution-extracts. The solution helps to extract one component from the mixture. In La Hague (France) and Sellafield (formerly Windscale, UK) the PUREX-method (Plutonium Uranium Recovery by Extraction) is used, which is based on a solution with 30% tributylenephosphate (TBP: C4H9O)3PO) and 70% kerosene.

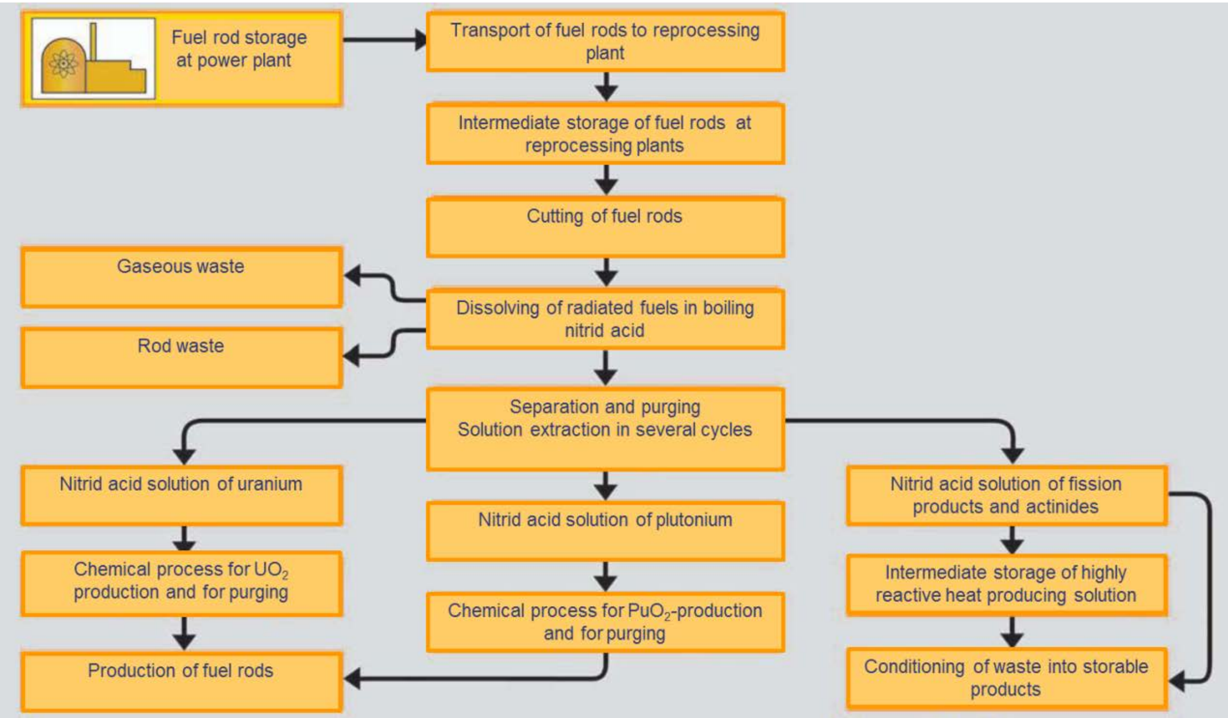

FIGURE 46: PROCESS STEPS DURING REPROCESSING (VOLKMER, 2004)

First, the burned fuel rods are removed from the water pool at the plant site, the status of burning is measured and the rod is brought to the decomposition cell. There the ends are removed and the rods are cut into pieces of 5 cm length. These pieces contain the uranium and decomposition products inside the casing of zirconium alloy which contains about 90% zirconium.

The pieces are solved in nitric acid (HNO3). This creates different nitrates of various composition metals. The addition of solvent results in the complex formation of uranium nitrate (UO2(NO3)2) and plutonium nitrate (Pu(NO3)4):

$UO_2^{2+} + 2\ NO_3^- + 2\ C_4H_9O)_3PO \rightarrow [UO_2(NO_3)_2 \cdot 2\ C_4H_9O)_3PO]_{org}$

$Pu^{4+} + 4\ NO_3^- + 2\ C_4H_9O)_3PO \rightarrow [Pu(NO_3)_4 \cdot 2\ C_4H_9O)_3PO]_{org}$

These nitrates together with the solvent create a layer of organic solvents and complexes while the nitrates of other metals remain in the aqueous HNO3-solution which decants. (see Figure 47).

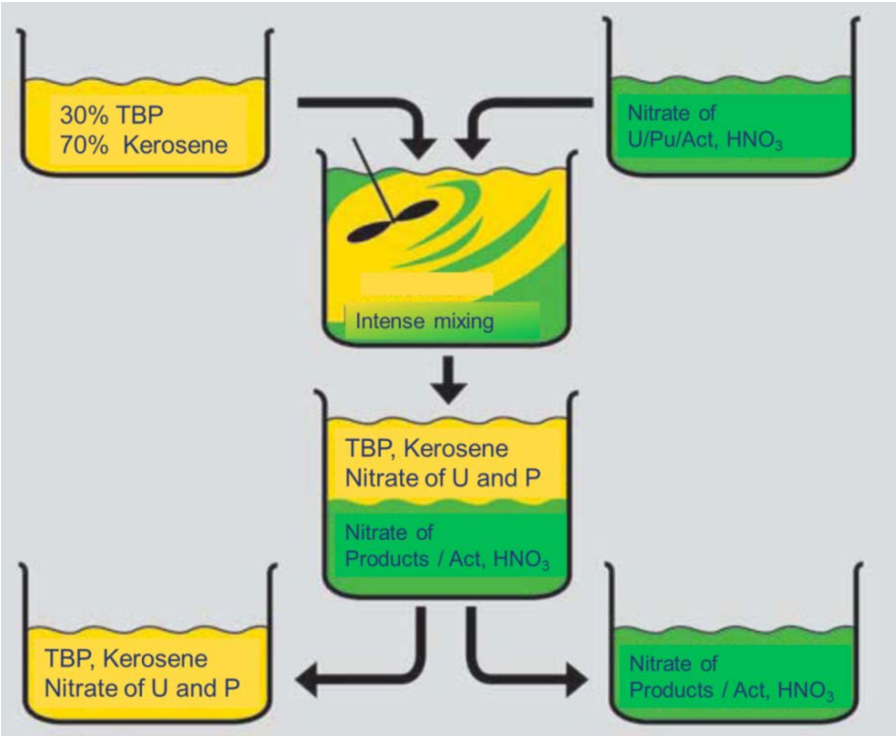

FIGURE 47: SEPARATION OF VARIOUS METALS FROM BURNED FUEL RODS BY MEANS OF THE PUREX-PROCESS (VOLKMER, 2004)

When a complete separation by various repetitions of the process is achieved, the uranium and plutonium nitrates are de-nitrified and converted to uranium and plutonium oxides. The highly radioactive parts of the fission products (e.g. 137Cs, 90Sr, 129I) are melt down into glass. Gaseous fission products (e.g. 85Kr) are emitted into the atmosphere. The total radioactive krypton inventory of the atmosphere has its origin in nuclear reprocessing and is a tracer which allows recalculating the total amount of reprocessed nuclear material. The separated plutonium is mixed with depleted uranium, natural uranium or reprocessed uranium to form so called mixed oxide fuel rods (MOX-elements). Further fission products are grouped into medium active waste and low active waste and grouted into concrete.

MOX-elements can be used as fuel in licensed reactors. The removed unburned uranium is also marketed under the name RepU or stockpiled for later uses. At world level only a few reactors have the license to use MOX-elements. This number has not yet chanced in recent years.

Theoretically, after burning in reactors MOX-elements again can be reprocessed. However, this increases the share of not further fissile plutonium isotopes and of other unrequested particles. Therefore, practically only burned uranium rods are reprocessed only for one time.

In January 2011 about 28 reactors or 6% of worldwide reactors had a license to burn MOX-elements, most of them in Europe. The “EURATOM SUPPLY AGENCY” (ESA) reported that the use of MOX-elements since 1996 probably has displaced the cumulative demand of about 17,032 t uranium inside EU. Apart from minor corrections this might represent the world total (OECD-NEA / IAEA, 2012, p. 109).

TABLE 9: MOX-PRODUCTION (T UEQ) (OECD-NEA / IAEA, 2012, 2010, 2008, 2006B)

Year	Belgium	France	Japan	Russia	UK
Until 2001	?	6,600	?	?	?
2002	?	1,000	?	1,300	
2003	?	1,000	50	1,300	
2004	86	1,110	15	1,300	
2005	0	1,160	0	?	
2006	0	1,160	0	?	22
2007	0	1,000	9	?	11
2008	0	1,008	4	?	?
2009	0	1,560	23	?	?
2010	0	1,560	37	?	?
2011*	0	1,560	2	?	?
Total	**523**	**17,158**	**671**	**?**	**?**

* estimate

TABLE 10: MOX-CONSUMPTION (T UEQ) (OECD-NEA / IAEA, 2012, 2010, 2008, 2006B)

Year	Belgium	Germany	France	Japan	Swiss	USA
Until 2001	396		?		677	0
2002	41		150		231	0
2003	0		150	6	272	0
2004	29	480	800	2	12	0
2005	28	480	?	4	108	0.1
2006	26	330	?	10.3	184	0
2007	0	220	?	0	94	0
2008	0	250	800	0	0	?
2009	0	210	800	135	0	?
2010	0	100	880	146	0	
2011*	0	100	960	0	0	
Total	**520**	**6,630**	**?**	**813**	**1,407**	**?**

* estimate

The MOX-production capacity at end 2004 was about 3,340 t U_{eq} (Diehl, 2013). In 2003 the Cadarache MOX fuel production plant in France ceased commercial production, but in 2007 the MELOX plant in Marcoule, France, was licensed to increase production to 1,560 tU_{eq} equivalent. In parallel the Belgium MOX-plant with 37 t HM capacity was closed at end 2006 (OECD-NEA / IAEA, 2012, p. 109).

Part of the agreement between Russia and USA to convert 68 t of warhead plutonium to fuel was the construction of a new conversion plant. This might have increased the world capacity by about 10 percent (USR, 2000).

The IAEA assumes in its Scenario calculation to 2050 (published in 2001) that the MOX-production might increase from below 2,000 t to about 3,600 t natural uranium equivalent and will remain stable until 2050.

2.4.3.2 REPU FROM SPENT FUEL ELEMENTS

Parallel to the separation of plutonium and its processing to MOX-elements in reprocessing plants also unburned uranium is regained from burned fuel rods. In principle, this uranium also can be used for the production of new fuel rods. Today this is predominantly performed in La Hague (France) and Sellafield (UK). However, this reprocessed uranium is almost not used in reactors. The reasons are that this uranium is enriched with ^{232}U and ^{236}U. The presence of ^{232}U in fuel rods results in a higher radioactivity which might harm the personnel. The presence of ^{236}U results in higher neutron absorption of the rods and would require a higher enrichment with ^{235}U in order to achieve the same reactivity for power production (Diehl, 2006).

France, for instance, produces 1,050 t burned uranium oxide fuel rods annually of which about 850 t are reprocessed in La Hague. This results in the recovery of 816 t uranium and 8.5 t plutonium. About 650 t of the uranium are stockpiled for long-term storage (Diehl, 2006). Since 2010 about 600

tU_{eq}/yr are recycled in four EdF reactors as reprocessed uranium total (OECD-NEA / IAEA, 2012, p. 109).

From today's view it seems highly unrealistic that the production and use of MOX-elements of RepU can be enhanced fast. Even the IAEA assumes in its scenario calculations that the contribution of MOX-elements could slightly increase from about 1,000 t in 2000 to 3,600 t in 2050. In parallel the contribution of RepU is seen to add another 2,500 t natural uranium equivalent in 2023 (see Table 11).

TABLE 11: REPROCESSED URANIUM PRODUCTION (T UEQ) (OECD-NEA / IAEA, 2012, 2010, 2008, 2006B)

Year	Belgium	France	Japan	Russia	UK
Until 2008	?	12,200	645	?	54,079
2009	0	800	0	?	1,689
2010	0	800	0	?	613
2011	0	1,000	0	?	?
Total	0	1,000	0	?	?

TABLE 12: REPROCESSED URANIUM CONSUMPTION (T UEQ) (OECD-NEA / IAEA, 2012, 2010, 2008, 2006B)

Year	Belgium	Germany	France	Japan	Swiss	USA
Until 2008	508	?	2,300	195	1,770	0
2008	0	950	300	0	320	?
2009	0	?	300	12	473	?
2010	0	?	600	8	291	
2011	0	?	600	0	309	
Total	508	?	4,100	215	3,163	?

2.4.4 URANIUM PRODUCTION FROM TAILINGS

"The mining of uranium ore as well as the reprocessing of burned fuel rods produce huge amounts of waste which still contains uranium. This waste is collected in so called tailings. Present projects show that the hereof potentially producible uranium amount might be very small and that its preparation will be very challenging" (quoted after Diehl (2006)).

A predominant source might be tailings at mines in South Africa. Here, uranium production predominantly is a byproduct from gold mining. The resulting huge tailings contain uranium in a very low concentration.

The total in South African tailings identified uranium amounts to about 60,000 t. The concentration is between 0.003 – 0.004%. Various recovery projects are announced and technical feasibility studies are prepared. However up to now not any economic meaningful project has been realized (Diehl, 2006).

One should turn the argumentation vice versa: That South Africa thinks on extracting this low grade uranium from old tailings might be an indicator that the easy time of uranium mining is over.

2.4.5 URANIUM PRODUCTION FROM RE-ENRICHED URANIUM STOCKS

Uranium enrichment unavailingly leaves large stocks of depleted uranium. This is stockpiled or partly used for other purposes as mentioned already.

The enrichment of one ton natural uranium to LEU with 4% ^{235}U produces about 900 kg depleted uranium with 0.3% ^{235}U. This adds up to about 45,000 t depleted uranium from the annual production of about 50,000 t natural uranium.

NEA estimates that at end 2008 worldwide about 1,700,000 t depleted uranium (0.3%) were produced from enrichment (OECD-NEA / IAEA, 2010). This might have increased to about 2 million t depleted uranium (0.3%) at year end 2012. Its further depletion to 0.14% ^{235}U would produce another 500,000 t U with 0.711% ^{235}U-concentration. Further depletion of the stockpile from 0.14% to 0.06% would add 140,000 t natural uranium equivalents. However, this process would require about 8 times as much energy (SWU) as the first production cycle with depletion from 0.3% to 0.14%.

This theoretical calculation gives an upper limit, as depleted uranium is already used for military or civil purposes, e.g. the production of MOX-elements or dilution of military HEU during arms conversion.

Russia e.g. uses uranium depleted to 0.3% to produce uranium with 1.5% ^{235}U concentration. This furthermore is mixed with HEU to produce LEU with 4.4% ^{235}U.

The production of 15,300 t LEU (4.4%) under the existing contract from 1993 consumes 500 t HEU (90%) and 14,800 t U (1.5%). The production of U(1.5%) converted 105,000 t U(0.3%) into 89,700 t U(0.1%). Therefore, only this conversion program consumed already105,000 t U (0.3%). The depleted 89,700 t U (01%) are stored. Table 8 gives an estimate of presumably at end 1999 still existing stockpiles of depleted uranium which still existed at end 1999.

TABLE 13: ESTIMATE OF AT END 1999 EXISTING STOCKPILES OF DEPLETED URANIUM (WIKIPEDIA, 2009; WISE, 2013C)

Country	Estimated quantity of U_{dep} (t)
USA	480,000
Russia	460,000
France	190,000
UK	30,000
Germany	16,000
Japan	10,000
China	2,000
Sout Korea	200
South Africa	73
World	~1,200,000

2.4.5.1 USA

Over the last 50 years the USA has accumulated more than 700,000 t depleted uranium which are stored in form of UF6. Of that amount about 10% (75,300 t) are depleted between 0.35 – 0.711%. The remaining 90% are already depleted far below 0.35%. The amount of natural equivalent which could be extracted from this stock is estimated with 25,950 t U (0.711%) under the assumption that the average depletion grade of the whole stock is 0.366%.

2.4.5.2 RUSSIA AND EUROPEAN UNION

Since 1996 URENCO and Eurodif deliver about 7,000 t Udep annually with a 235U-content of 0.3-0.35 % to Rosatom. Rosatom converts these quantities at favorable conditions to natural uranium equivalent. About 2,200 t natural uranium equivalent are shipped to Europe annually.

The quantities delivered from Russia to Europe are given in Table 14.

On 2007 June 23rd, Russian officials declared that the agreement with Eurenco and Eurodiff will not be extended. The claimed reason was that under present economic conditions this agreement is no longer meaningful as excess capacity has ceased (NTI, 2007).

At end 2003 Russia had depleted and stored a total of 545,000t U_{dep} –which partly are depleted to below 0.1%. Out of that, about 100,000 t U_{dep} are from EU deliveries, the rest is due to domestic depletion. This amount could be used in future fast breading reactors

TABLE 14: QUANTITIES OF NATURAL URANIUM EQUIVALENT DELIVERED FROM RUSSIA TO EU, WHICH FORMERLY WERE SENT FROM EU TO RUSSA AT 0.3-0.35% DEPLETION (OECD-NEA / IAEA, 2012, P. 112, 2008, P. 81, 2006B, P. 69).

Country	Estimated quantity of U_{dep} (t)
USA	480,000
Russia	460,000
France	190,000
UK	30,000
Germany	16,000
Japan	10,000
China	2,000
Sout Korea	200
South Africa	73
World	~1,200,000

2.4.6 SUMMARY AND PRODUCTION IAEA PRODUCTION SCENARIO

Table 15 summarizes the above discussed amounts of uranium, supplemented with reported industrial uranium storage. This quantification is not complete; however it should be close to the total number. From the data it becomes apparent that by far the largest potential with more than 200,000 tU_{eq} comes from the possible enrichment of depleted uranium tailings. However, the economic and technical conditions are very unfavorable. Therefore it is highly probable that only very small amounts of these tailings could be used in practice. The US Department of Energy assumes that within the next 20 years only about 26,000 tU_{eq} might be produced that way. This would correspond to an annual contribution of about 1,300 tU_{eq}.

The US-DoE assumes that from piled stocks of 58,931 t U (2008) (DOE, 2008) between 500 t U and up to 4,000 t U annually could become available for the market (Szymanski, 2009).

The IAEA performed a scenario calculation of uranium production and supply until 2050, including secondary uranium sources. The results are shown in Figure 48and Table 16 (IAEA, 2001b).

This scenario assumes that the availability of HEU from Russian arms conversion still continues beyond 2013. However, the corresponding contract ceases and was not continued or substituted by a new contract. Therefore the data in Figure 48and Table 16 are adapted by 2,000 t/year supply from military HEU stocks beyond 2014.

TABLE 15: SUMMARY OF IDENTIFIED POSSIBLE QUANTITIES URANIUM QUANTITIES FROM SECONDARY SOURCES INCLUDING INDUSTRIAL STOCKS

Country	Origin	t	Source
Argentina	Natural uranium	52	(OECD-NEA / IAEA, 2012)
Australia	Stockpile at Mine Ranger	20,900	(AUA, 2008)
Bulgaria	LEU	81	(OECD-NEA / IAEA, 2012)
Lithuania	LEU	47	(OECD-NEA / IAEA, 2012)
Hungaria	Natural uranium	5	(OECD-NEA / IAEA, 2012)
Portugal	Natural uranium	168	(OECD-NEA / IAEA, 2012)
Korea, Rep.	LEU	6,000	(OECD-NEA / IAEA, 2012)
Korea, Rep.	Natural uranium	2,000	(OECD-NEA / IAEA, 2012)
Spain	LEU	611	(OECD-NEA / IAEA, 2012)
Switzerland	Natural uranium	1674	(OECD-NEA / IAEA, 2012)
	LEU	997	(OECD-NEA / IAEA, 2012)
Turkey	Natural uranium	2	(OECD-NEA / IAEA, 2012)
USA DoE	HEU (unallocated)	12,485 t Ueq	(DOE, 2008)
	HEU (allocated)	2,202	(DOE, 2008)
	NU (UF6)	5,156	(DOE, 2008)
	Russian NU (UF_6)	12,440	(DOE, 2008)
	Off-Spec Non-UF_6	2,900	(DOE, 2008)
	U_{dep} (UF_6) ca. 75,300 t U_{dep}, (>0,35%)	25,950	(DOE, 2008)
	U_{dep} (UF_6) ca. 630,000 t DU (<0,35%)	60,000**	(DOE, 2008)und eigene Berechnung
	Pu Conversion(34 t) (MOX)	4,080	(USR, 2000)
USA – Com.	Natural uranium	36,381	(OECD-NEA / IAEA, 2012)
	LEU	26,982	(OECD-NEA / IAEA, 2012)
Russia	HEU (Conversion)	44,400	Eig. Berechnung
	Pu Conversion (34 t) (MOX)	4,080	(USR, 2000)
	U_{dep} (UF_6) ca. 545,000 t U_{dep}, usable:	~130,000***	Eig. Abschätzung
	LEU	100	
EU	MOX-stocks	6,045	Ber. Nach (OECD-NEA / IAEA, 2008)
Total		**401,662**	
Total	**without U_{dep}**	**~216,000**	

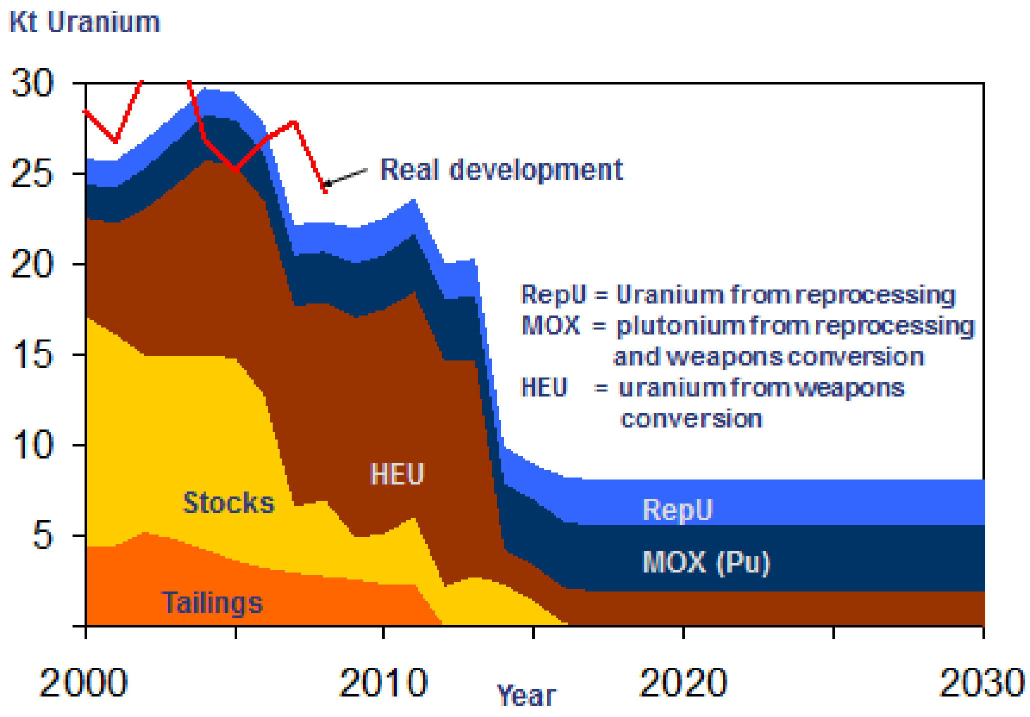

Figure 48: (adapted) IAEA-supply Scenario for uranium supply from secondary sources until 2030. THE IAEA –SCENARIO WAS CORRECTED, AS THE CONVERSION OF HEU FROM RUSSIAN MILITARY STOCKS WILL CEASE IN 2013.

TABLE 16 IAEA SUPPLY SCENARIO WITH URANIUM FROM SECONDARY SOURCES (IAEA, 2001B)IN T NATURAL URANIUM EQUIVALENT (T UEQ)

Year	HEU stocks	Company stocks	Russian stocks	MOX	RepU	tailings	Total
2000	5,400	5,550	7,100	1,900	1,400	4,500	**25,850**
2001	6,200	5,294	6,300	1,900	1,500	4,500	**25,694**
2002	8,000	5,289	4,500	2,300	1,500	5,200	**26,789**
2003	9,300	6,447	3,700	2,400	1,500	4,850	**28,197**
2004	10,700	7,876	2,900	2,500	1,500	4,250	**29,726**
2005	10,600	8,210	3,000	2,500	1,500	3,650	**29,460**
2006	10,700	6,573	2,900	2,600	1,700	3,300	**27,773**
2007	11,100	1,105	2,500	2,800	1,700	3,000	**22,205**
2008	10,900	-2,064	2,100	2,800	1,700	2,800	**18,236**
2009	12,100	-1,364	900	3,000	2,000	2,650	**19,286**
2010	12,400	1,867	900	3,000	2,000	2,350	**22,517**
2011	12,400	2,822	900	3,200	2,000	2,350	**23,672**
2012	12,400	1,370	900	3,400	2,000	0	**20,070**
2013	11,900	-1,869	900	3,600	2,000	0	**16,531**
2014	11,900	-2,327	0	3,600	2,000	0	**15,174**
2015	11,900	-1,373	0	3,600	2,000	0	**16,127**
2016	11,900	160	0	3,600	2,500	0	**18,160**
2017	11,900	0	0	3,600	2,500	0	**18,000**
2018	11,900	0	0	3,600	2,500	0	**18,000**
2019	11,900	0	0	3,600	2,500	0	**18,000**
2020	11,900	0		3,600	2,500	0	**18,000**
2021	11,900	0		3,600	2,500		**18,000**
2022	8,000	0		3,600	2,500		**14,100**
2023	0	0		3,600	2,500		**6,100**
Total	**247,300**	**43,566**	**39,500**	**73,900**	**48,000**	**43,400**	**495,667**

3 URANIUM SUPPLY SCENARIOS

3.1 URANIUM SUPPLY SCENARIOS DEVELOPED FOR THE EHNUR PROJECT

In the course of the project supply scenarios were created for two different reference dates. One at the beginning of 2009 referring to the Uranium Redbook 2009 (OECD-NEA / IAEA, 2010) and before the Fukushima accidents; the other one, very recent, using the resource basis at the end of 2012 and the Uranium Redbook 2011 (OECD-NEA / IAEA, 2012) with some adoptions, thus after the Fukushima accidents[27].

The scenarios are presented for the categories of Reasonably Assured and Identified Resources and compared with the demand scenarios of the abovementioned Redbooks, which are actually very similar except for a higher low-demand scenario in the Redbook 2011 (see e.g. Figure 51)

The scenarios

- assume no further delays of the startup of planned mines (one exception in the RAR2 scenario)
- do not accout for secondary resources (with few exceptions)
- assume the mines being mined until all of their recoverable resources are depleted, which is an overestimation as mining plans and minig licenses are usually shorter
- include no differences in cost categories (low-cost mines are not favoured); resources of all cost categories are included.
- all represent an average capacity factor of 80%.

Thus these scenarios can rather be considered an upper limit for short and medium-term development of uranium mining.

3.1.1 IR SCENARIOS

The IR scenarios represent the highest production scenarios created. It implies that all of the Identified resources are converted to RAR and the Reserves and are mined. Practically all of the mines operate past their current mining plans. Therefore these are actually seen as unrealistic by the author, in particular in the short and medium-term, especially as the growth of global production – if not by other aspects mentioned before – will be hampered by the availability of secondary resources, and thus less interest in putting uranium mines in operation. Nonetheless they might be useful on discussion on long-term perspectives.

The **IR Scenario 2009-1** (Figure 49) shows production even exceeding demand in the years 2015 to 2020. This mainly results from the initially planned expansion of the Olympic Dam mine, which was

[27] Note that the scenarios were created between 2011 and early 2013. Especially for the startup plans of new mines more information was available than in the 2009 Redbook edition.

cancelled in late 2012[28]. The **IR Scenario 2009-2 (**Figure 50) represents the same scenario excluding the Olympic Dam expansion. Both IR 2009 scenarios stop fulfilling the IAEA high demand scenario around 2020, never reaching the high demand again, peaking around 2035 but providing uranium for the low demand until almost 2060.

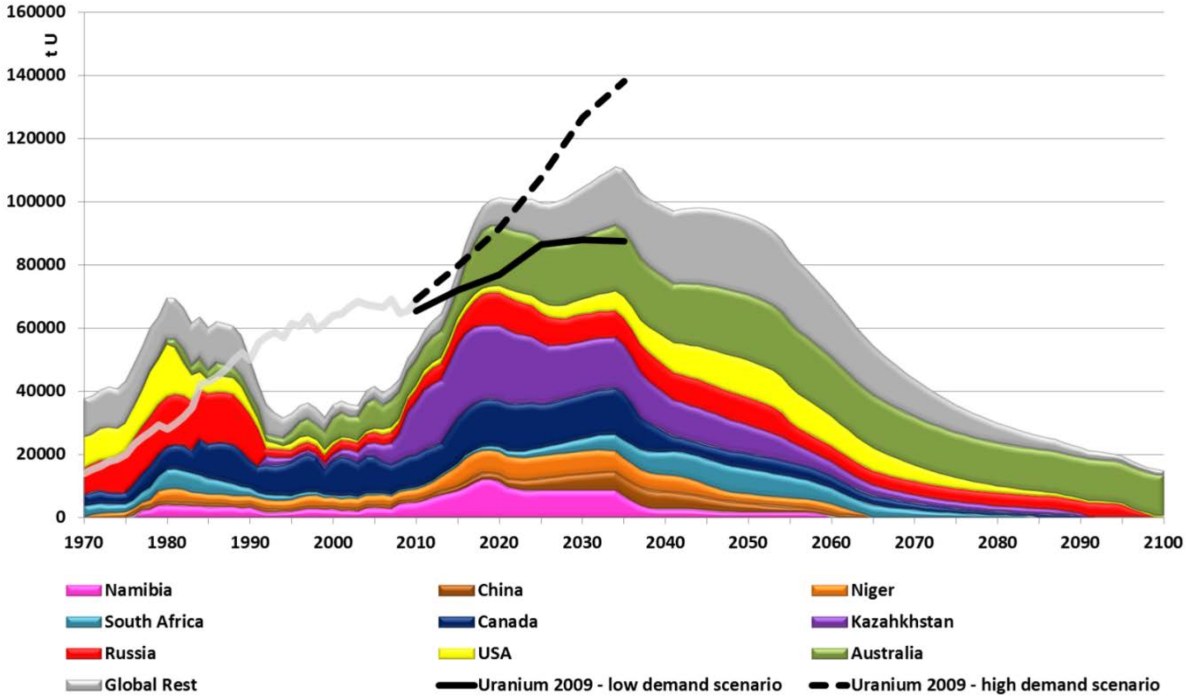

FIGURE 49: IR SCENARIO, RESOURCEBASE 2009 – 1

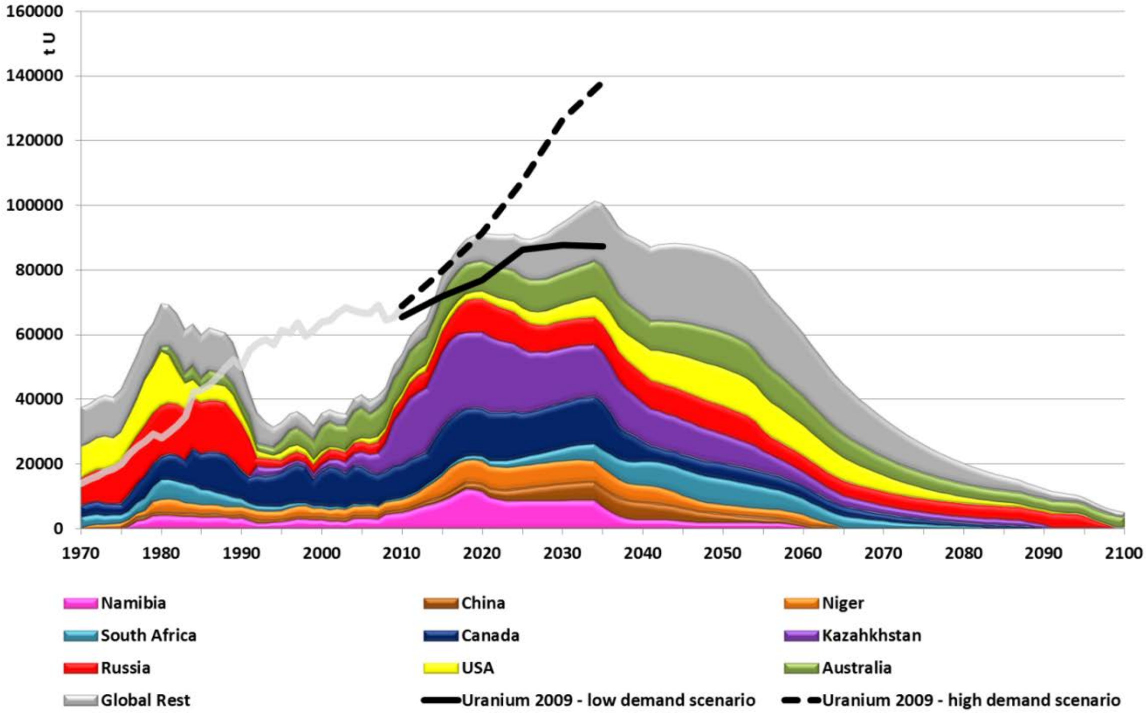

FIGURE 50: IR SCENARIO, RESOURCEBASE 2009 – 2

[28] See Annex II - Australia.

In comparison the IR Scenario 2012 (Figure 51) already shows a smaller increase in production in the coming years, reflecting some impacts of the Fukushima accidents and some “normal” delays in startup. This scenario includes an expansion of Olympic Dam in 2020, but only doubling instead of quadrupling. The scenario separates from the high demand scenario in 2025 providing an output from about 110,000 tU for the following 30 years. While the maximum global production is roughly the same, this output can be obtained for a longer timeframe due to the increased overall resources. All of the IR scenarios show a typical bell-shaped decline past 2050.

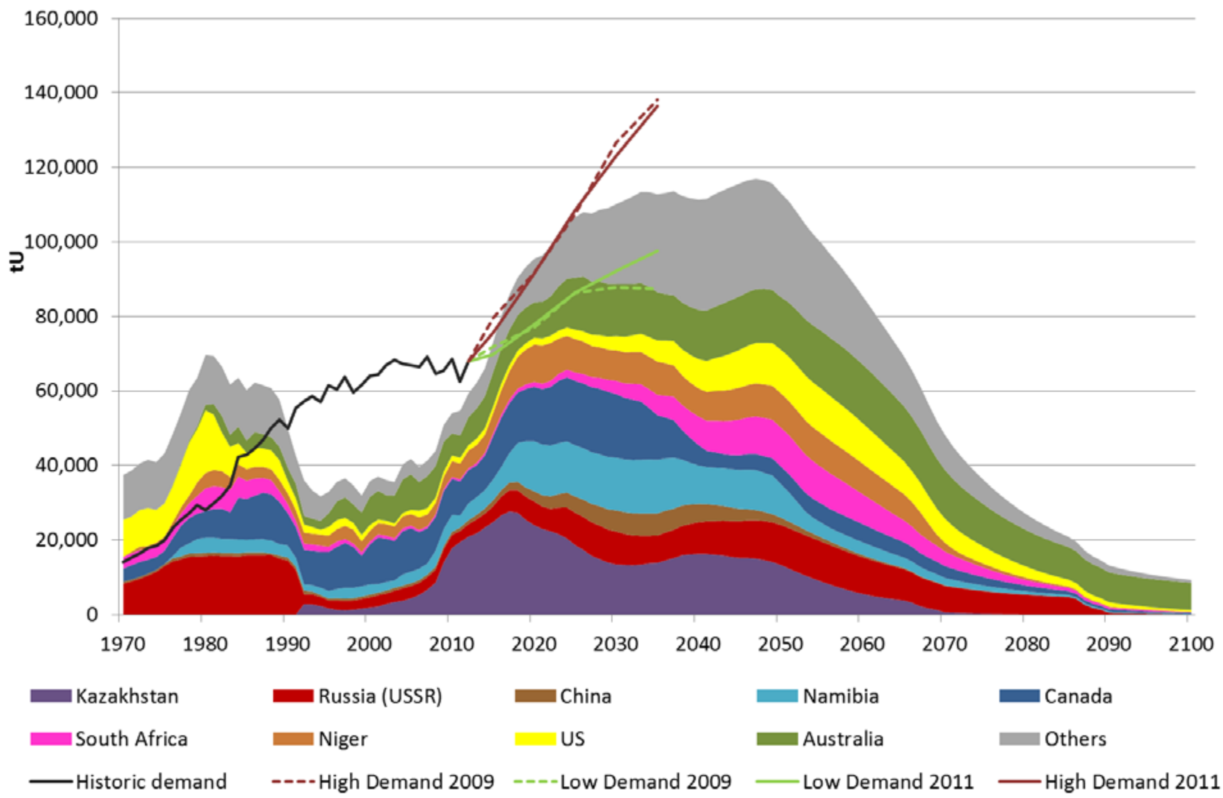

FIGURE 51: IR SCENARIO, RESOURCEBASE 2012

3.1.2 RAR SCENARIOS

The RAR can be considered more realistic in the short and medium-term development of production, but still optimistic. The increase in global production is slower due to the depletion of some mines. All the RAR scenarios still assume an expansion of Olympic Dam to double capacity from 2020.

While in the RAR scenario 2009 (Figure 52) can cover the IAEA low demand scenario between 2015 and 2020 with primary uranium, with production peaking in 2020. Based on the 2012 resource, startup and capacity evaluation (Figure 53) the primary production never exceeds the IAEA low demand scenario. Once again a minor growth in production capacities and a shift of the peak production further to future can be observed. Figure 54 includes some estimates on secondary resources, allowing an intermediate scenario to be covered until 2025. Based on the 2011 RAR figures, the low demand scenario from the IAEA in 2011 would require almost 30,000 tU to be recovered from secondary or unconventional resources by 2035.

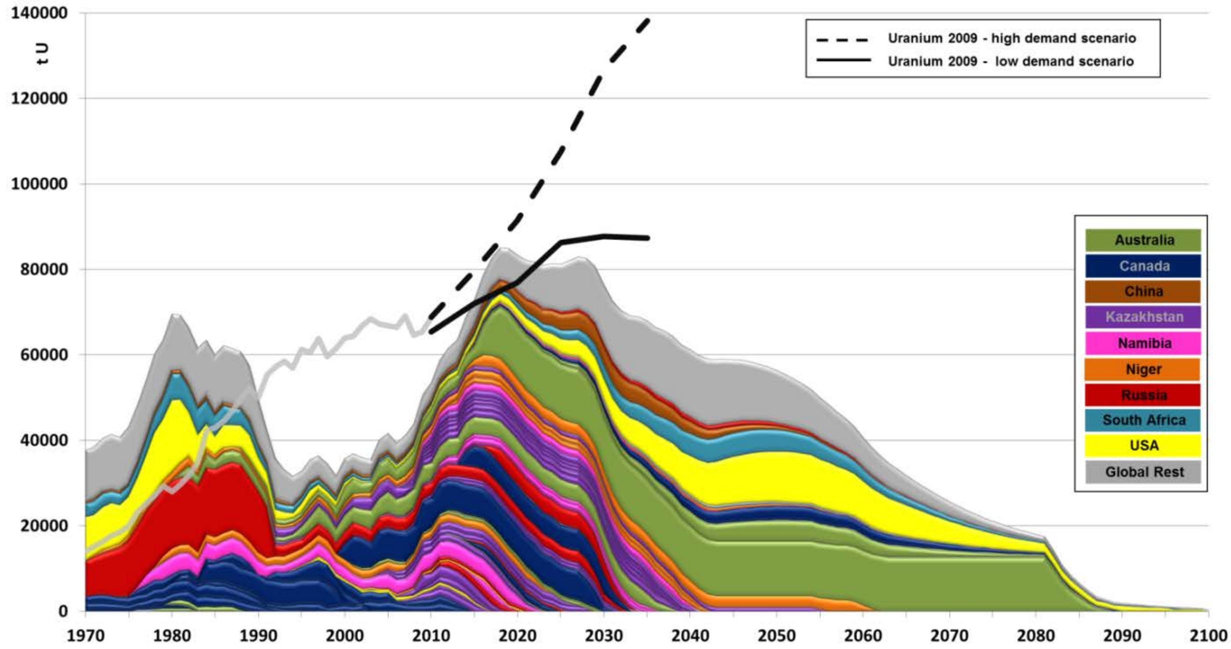

FIGURE 52: RAR SCENARIO, RESOURCEBASE 2009

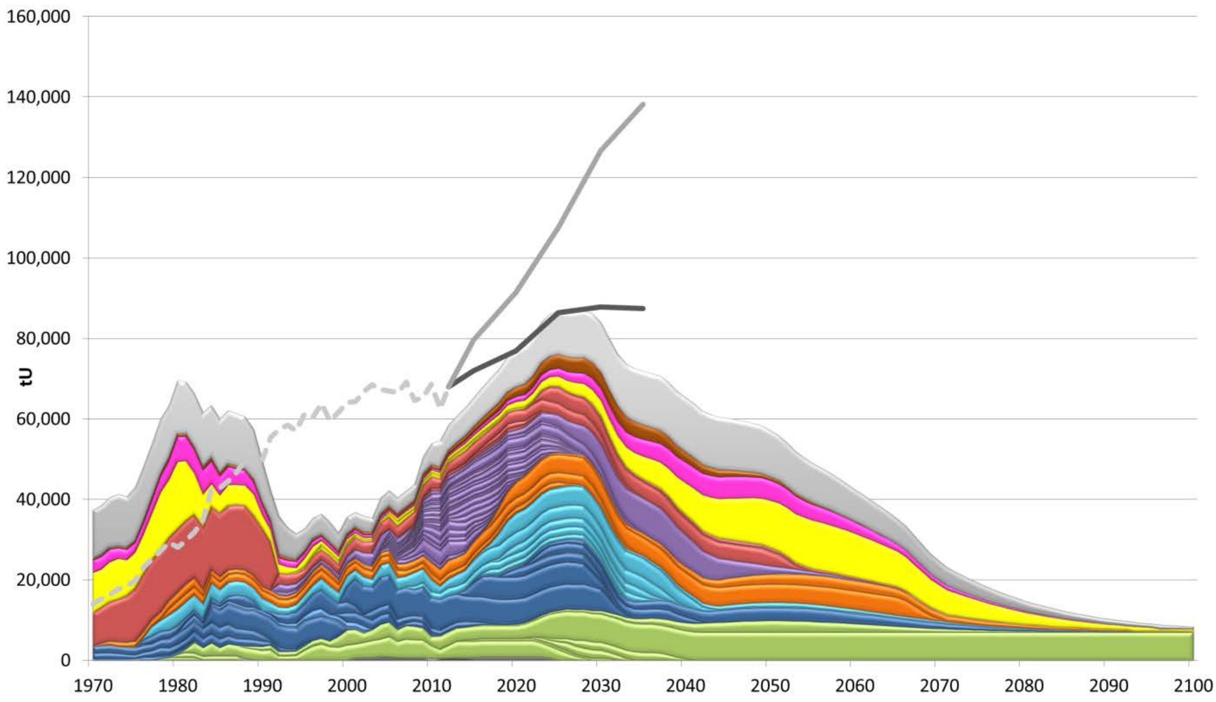

FIGURE 53: RAR SCENARIO, RESOURCEBASE 2012

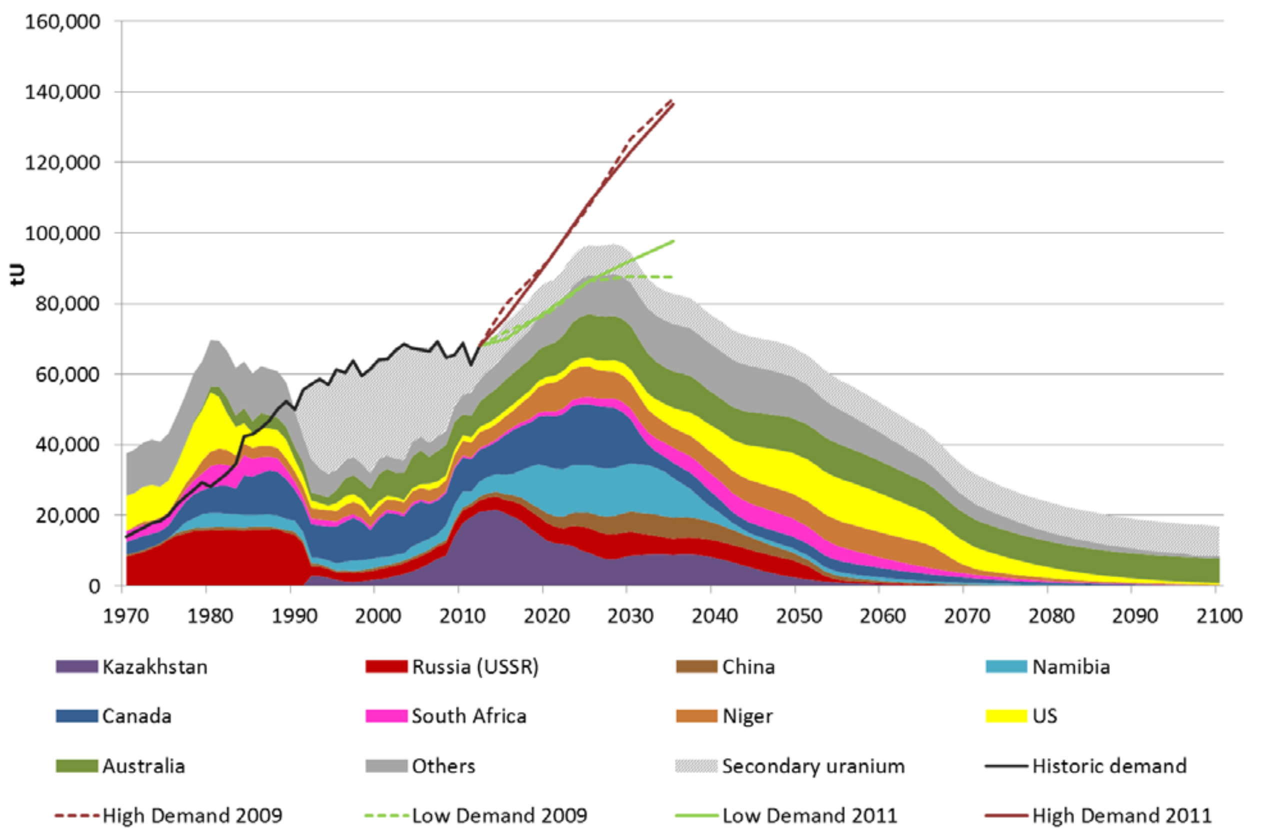

FIGURE 54: RAR SCENARIO INCLUDING SECONARY RESOURCES, RESOURCEBASE 2012 THE SECONDARY RESOURCES ARE BASED ON FIGURE 48 AND CONTINUED UNTIL 2100. ESPECIALLY FOR THE HEU IT CANNOT BE EXPECTED TO BE AVAILABLE VERY LONG, BUT TO SOME EXTENT THIS MIGHT BE COMPENSABLE BY UNCONVENTIONAL REOURCES, WHICH ARE NOT CONSIDERED.

3.1.3 RAR SCENARIO 2

The second RAR scenario presented contains some less optimistic frame conditions. It shows the major dependence of future on a few large projects. The assumptions made affect only four (future) mines.

- No expansion at Olympic Dam
- No development of the Elkon deposit
- Husab and Cigar Lake producing at half of their planned capacity.

In this scenario primary uranium cannot even provide enough uranium for the low demand scenario. Adding secondary resources can cover this demand until 2025. Including unconventional resources the demand until 2030 can be covered.

This primary production scenario can be considered as the most realistic one, as history has shown that delays, capacity losses and decisions not to develop deposits have to be expected.

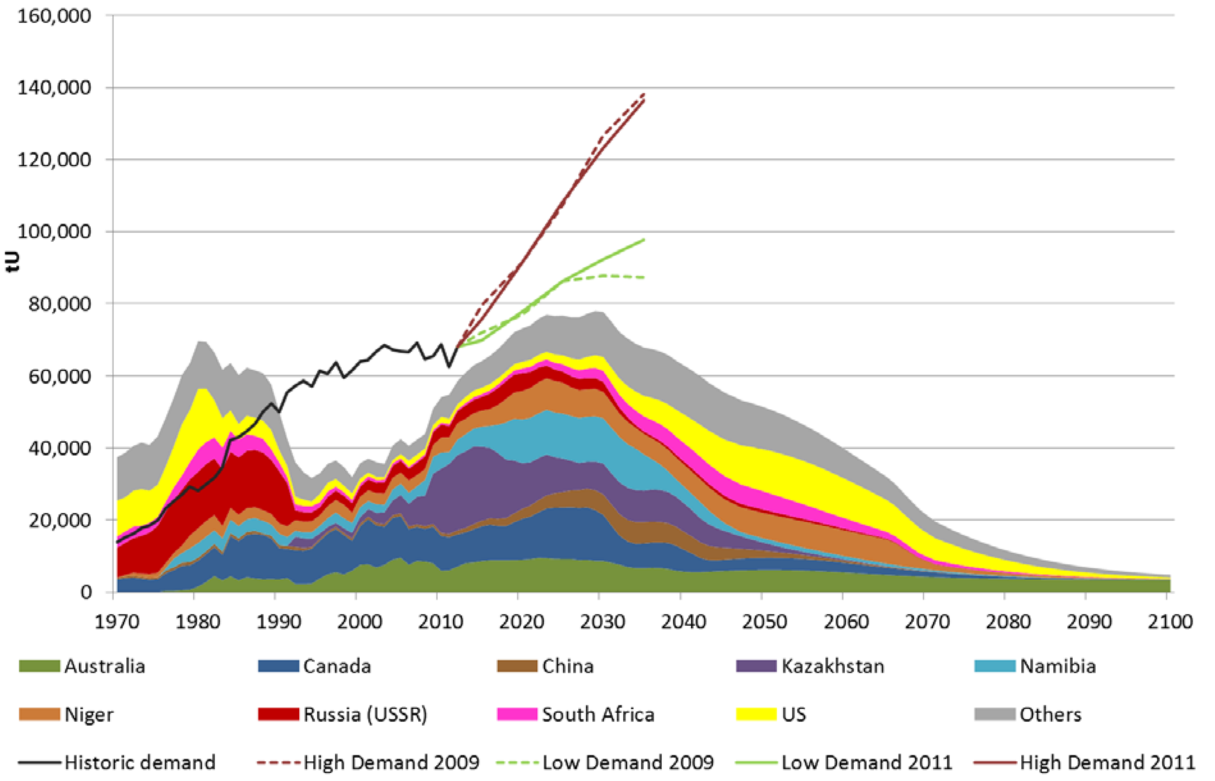

FIGURE 55: RAR SCENARIO 2 – RESOURCEBASE 2012

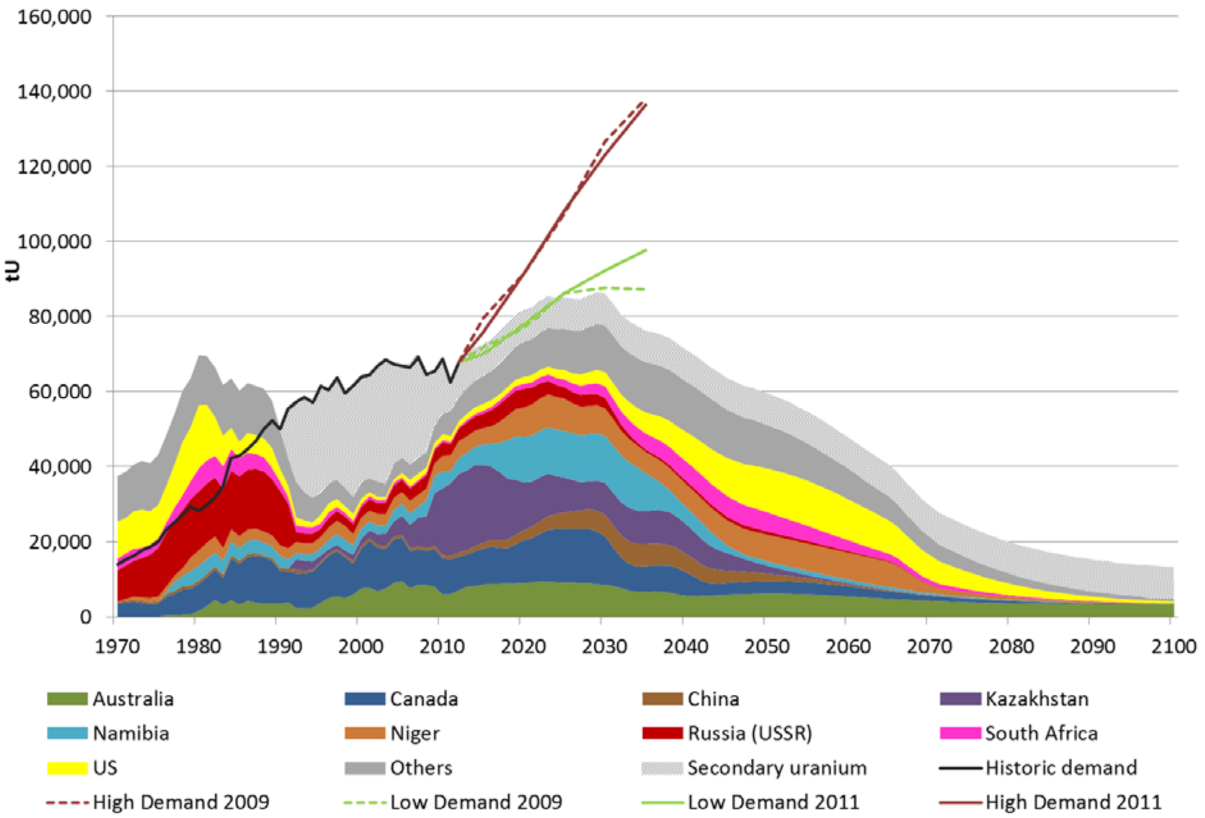

FIGURE 56: RAR SCENARIO 2 INCLUDING SECONARY RESOURCES – RESOURCEBASE 2012 THE SECONDARY RESOURCES ARE BASED ON FIGURE 48 AND CONTINUED UNTIL 2100. ESPECIALLY FOR THE HEU IT CANNOT BE EXPECTED TO BE AVAILABLE VERY LONG, BUT TO SOME EXTENT THIS MIGHT BE COMPENSABLE BY UNCONVENTIONAL REOURCES, WHICH ARE NOT CONSIDERED.

3.1.4 NECESSARY NEW DISCOVERIES

The next paragraphs shall provide a short, simplified discussion on the new uranium discoveries needed to supply IAEA high and low demand scenarios until 2100 shall be made[29].

To fulfill the low demand scenario until 2100 (assuming constant demand from 2035) an additional 4 to 4.9 Mio t U[30] have to be ascertained as RAR, and also fully mined and used as fuel within this timeframe. For the high demand scenario additional 7 – 7.9 Mio t U are necessary until 2100. Therefore between 45,000 t U and 89,000 t U s have to be found per year in total to fulfill those needs.

From 1997 to 2009[31] roughly 52,000 t of new RAR were identified on average per year. Provided that current rates of new detections can be maintained, this means that, based on RAR <260 USD/kgU, only IAEA Low Demand Scenario might be supportable with ^{235}U fuel in a long term. On the other hand, increase of the nuclear energy share towards a high demand scenario does not seem feasible, even with a growing resource basis.

TABLE 17: NEW RAR DISCOVERED IN THE PAST 14 YEARS

	Low demand scenario IAEA 2011	High demand scenario IAEA 2011
Lack of U until 2100	4 - 4.9 Mio t U	7 - 7.9 Mio. t U
Average new finds per year necessary based on 2011 RAR <130 USD/kgU +	55 kt U	89 kt U
Average new finds per year necessary based on EHNUR RAR Scenario (RAR <260 USD/kgU)	52 kt U	85 kt U
Average new finds per year necessary based on 2011 RAR <260 USD/kgU	45 kt U	79 kt U
Avg. yearly RAR growth 1997-2009* RAR <130 USD/kgU	52 kt U	
Avg. yearly RAR growth 1997-2007* RAR <130 USD/kgU	36 kt U	

* The average yearly growth is based on resources < 130USD/kgU as the category < 260 USD/kgU was introduced in 2009.

+ Assuming all the RAR can be mined.

29 Not accounting for unconventional and secondary resources.

30 Depending on the cost category and the production scenarios.

31 Note that there was a large growth in 2009 and in the <260 USD/kgU category. As there are only two values for this category no representative average can be derived.

3.2 OTHER URANIUM SUPPLY RELATED PUBLICATIONS

For this chapter other efforts to evaluate the future uranium supply situation were collected. Some main conclusions are cited, so the reader put them into relation with our scenarios.

First some results from the industry itself are presented, followed by some publications of the scientific community.

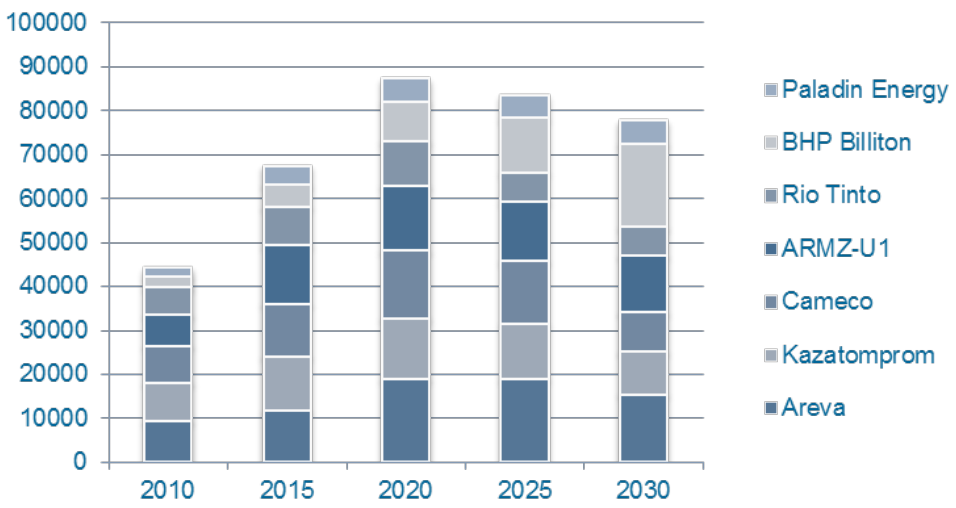

FIGURE 57: URANIUM PRODUCTION FORECAST BY LEADING COMPANIES (BOYTSOV, 2012)

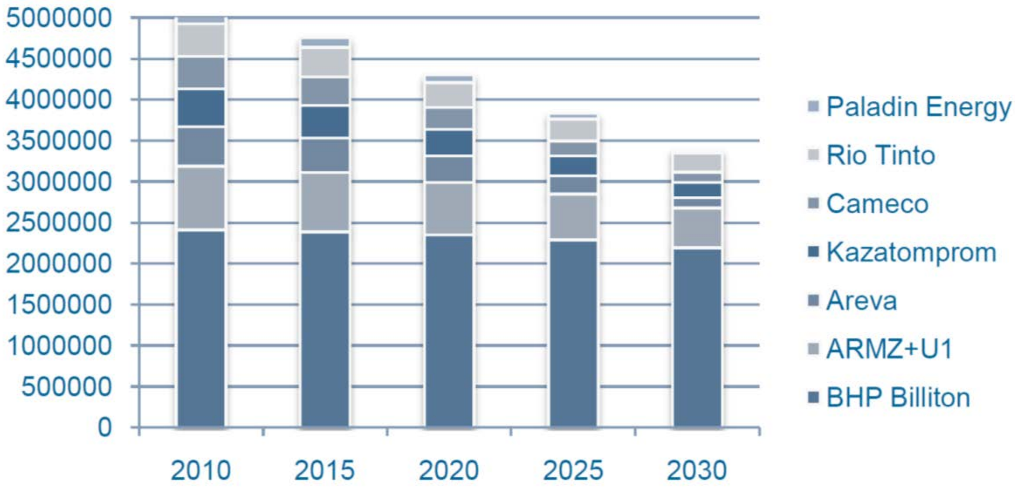

FIGURE 58: DEPLETION OF U RESOURCES BY LEADING COMPANIES (BOYTSOV, 2012)

At Atomexpo 2012 Alexander **Boytsov** gave a speech on “Sustainable Development of Uranium Production –Time Challenge”. Figure 57 and Figure 58 were presented alongside with the conclusions:

- *“Aggregated U production in 2012 –2030 estimated at 1,5 MtU, which is 24% of total resources and 40% of resources below US$80/kgU category*
- *U resources of primary uranium mines will be decreased by 2030 more than two fold, more than a half of the remaining U resources will be in the Olympic Dam (copper is main)*

- *After 2020, uranium market may face shortage of low cost U resources needed to maintain production.*
- *It is necessary to intensify uranium exploration aimed at discovery new low cost uranium resources."*

Figure 58 shows the two thirds of the resources of the main companies remaining in only one Deposit (Olympic Dam, owned by BHP Billiton).

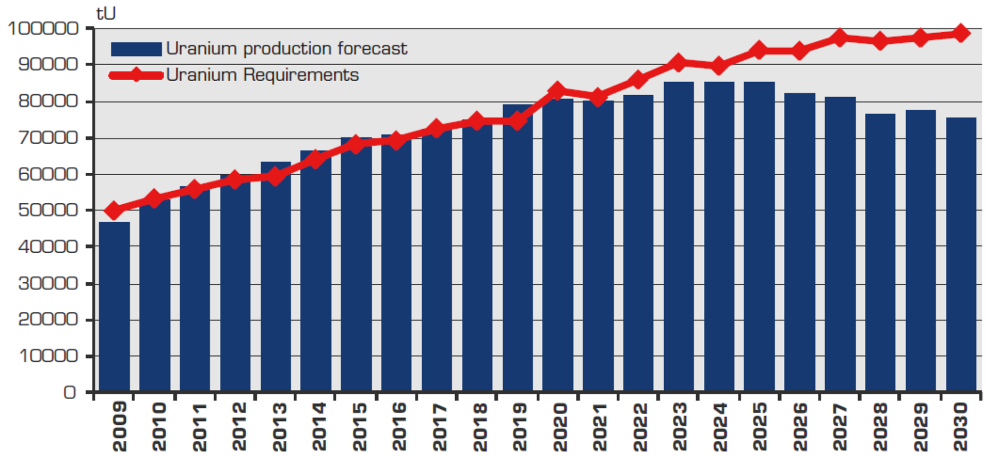

FIGURE 59: URANIUM REQUIREMENTS AND PRODUCTION FORECAST (BOYTSOV, 2012)

AtomRedMetZoloto (ARMZ), the Russian state mining company, presented the figure above (Figure 59) in a booklet from 2011 (ARMZ, 2011) describing the company. The following stages of uranium Mining development are stated:

"2010-2020 – production covers requirement

Post 2020 – uranium production capacity shortage

Post-2025 – decline in production volume and capacity shortage"

The **World Nuclear Association (WNA)** is an international organization supporting companies of nuclear industry and promoting nuclear energy. In the 2011 report "The Global Nuclear Fuel Market: Supply and Demand 2011-2030" (WNA, 2011) the two scenarios from Figure 60 are presented:

"Upper case. The market can be satisfied by rising supply. The supply and demand are very much in balance for the period to 2025. In the final years, additional new mines will be needed.

Lower case. With much lower primary uranium supply, the persistence of secondary supply means that lower case demand is covered even after the down-blended HEU from Russia drops out after 2013. But the lack of new mine development and closures of existing mines means that only the lower demand scenario can be covered to 2030."

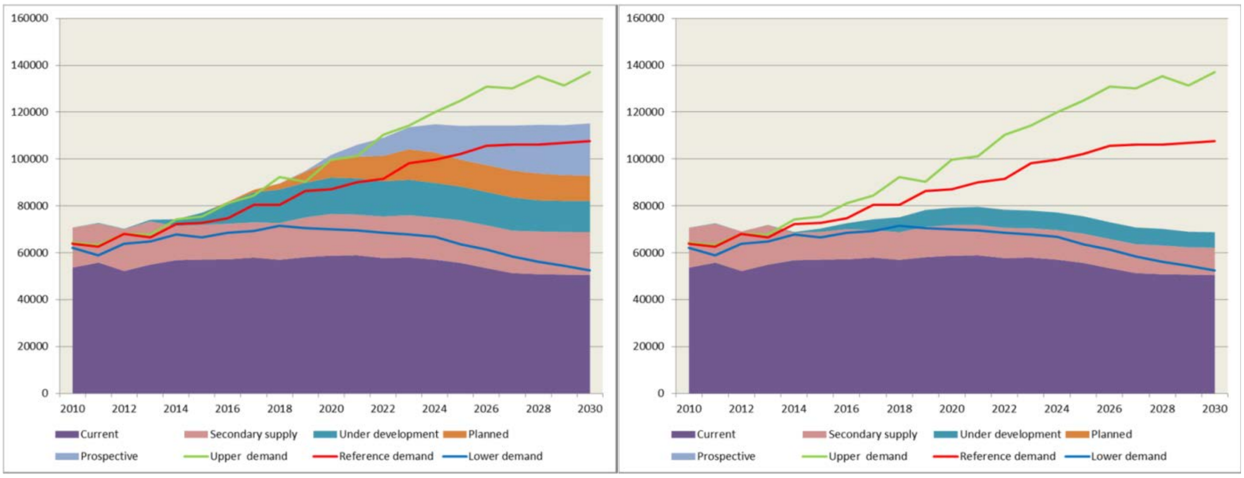

FIGURE 60: UPPER AND LOWER CAS SUPPLY - DEMAND FROM THE WNA MARKET REPORT (WNA, 2011)

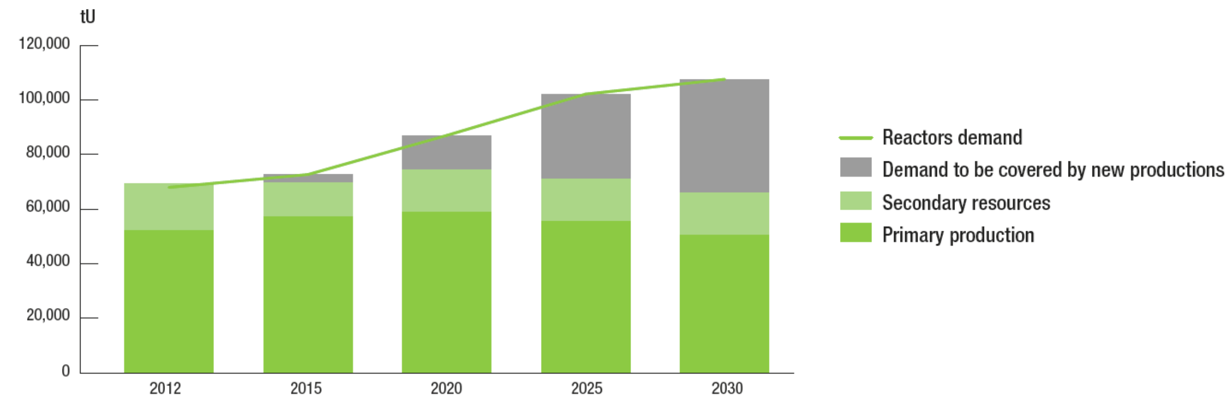

FIGURE 61: WORLD DEMAND AND SUPPLY (AREVA, 2013)

The 2012 Reference Document of the **French Company Areva** (Areva, 2013) states the following on page 69, concerning short-term development of uranium production.

"Demand has risen over the past five years in terms of volume, reflecting increasing load factors, connection to the grid of a few new reactors, and the growing number of power upratings at existing reactors. In addition, some utilities, seeking to build strategic inventories in line with their investments in new nuclear capacity, particularly in Asia, have contributed to rising demand in recent years. The forecasts for increased global demand by 2020 were revised downwards following the Fukushima accident. However, market growth is still expected, with demand 28% greater in 2020 than in 2012 according to the World Nuclear Association (WNA). …….. Prospects for an increase in global production over the medium and long terms have declined: some projects have been postponed or cancelled, capital programs have been cut, and the global exploration effort is down, particularly on the part of junior mining companies with limited access to capital. World production covers about 90 % of uranium consumption; the balance is satisfied by secondary sources (mainly from excess inventories held by the DOE, material from diluted HEU, the use of MOX fuel and recycled uranium). The HEU program, which brings about 7,500 metric tons in secondary resources to the market, will terminate at the end of 2013.The increase in production will mainly result from the development of new mining projects, off setting production decreases and planned mine closures. Uranium producers' quick decisions to postpone or cancel the start of production at mining projects reflect a lesser increase in demand after the Fukushima accident."

Frimmel and Müller (2011) conclude the following for future uranium supply in a paper on the reliability of estimates of mineral resource availability:

"The predicted net deficit for the high-case scenario could be in parts reduced if the Jabiluka Deposit in northern Australia can be mined. Currently, this deposit, which contains a resource of some 196kt U3O8, is put on hold for socio-political reasons. The current owner, Rio Tinto, intends to bring Jabiluka into production once the nearby Ranger deposit is exhausted (projected for 2023). This could add c. 5 to 6 kt U3O8/a (if one includes the similar Koongarra project) to the global production. Further potential lies in the Elkon District, where only about 41 of the overall resource of 370 kt U3O8 would have been mined by 2035. There the limiting factor is production capacity, designed to be 5 kt U/a. All in all some extra 15 kt U/a could be possible for the period 2030 to 2035. This would still leave a deficit of 70 to 80 kt U3O8/a from 2030. Such a deficit as projected for the high-case scenario would invariably lead to a price increase, which in turn could move several resources into the reserve category. This raises the question whether a decreasing supply/demand ratio and consequently higher prices will not only intensify exploration but also result in a corresponding increase in new discoveries and in the overall reserve base. Although such a direct relationship between increase in the commodity's price, exploration expenditure and new discoveries that can expand the reserve base is a very common perception, it does not hold up to scrutiny as elaborated upon in the next section."

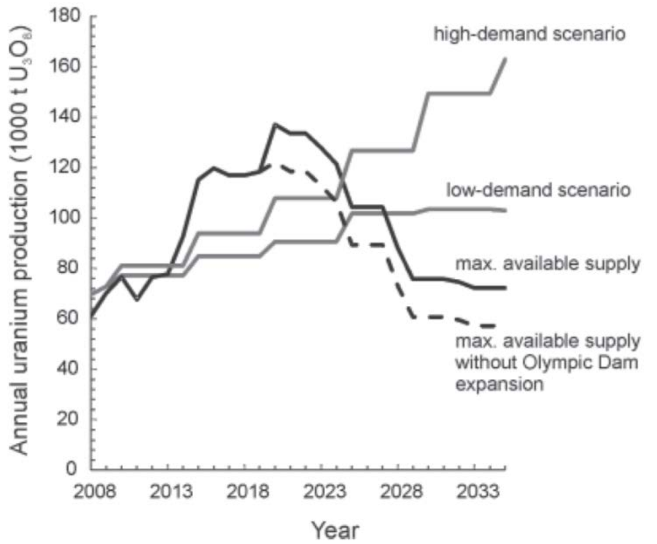

FIGURE 62: FORECAST UNTIL 2035 OF MAXIMAL AVAILABLE U FROM MINING COMPARED WITH LOW- AND HIGH-CASE DEMAND SCENARIOS (IN 5-YEAR STEPS) AS PREDICTED BY OECD/IAEA (FRIMMEL AND MÜLLER, 2011)

"A detailed analysis of the future availability of uranium from primary sources, i.e. ore deposits, revealed that in the medium-term the expected demand can be met. In fact, a considerable overcapacity is prognosticated for the next 10 to 15 years if all projects will be realised as currently planned (Fig. 12). Carrying forward of these overcapacities into the late 2020s and early 2030s will offset a modelled gap between demand and supply but from the mid-2030s a growing shortage of U as fuel for nuclear reactors is forecast if the global nuclear power capacity will be expanded as planned."

In a very recent publication **Hall and Coleman (2013)** expect challenges for the uranium supply in the near future.

"Production of resources in both operating and developing uranium mines is subject to uncertainties caused by technical, legal, regulatory, and financial challenges that combined to create long timelines between deposit discovery and mine production. This analysis indicates that mine development is proceeding too slowly to fully meet requirements for an expanded nuclear power reactor fleet in the near future (to 2035), and unless adequate secondary or unconventional resources can be identified, imbalances in supply and demand may occur."

"Mine production may not keep pace with demand because (1) the time between the delineation of a deposit and the time when it is first mined can lag by as much as 15 years ; (2) exploration in some regions is insufficient to keep production growing at reasonable rates; (3) infrastructure inadequate to support the economic milling of the ore may limit extraction; and (or) (4) future exploratory drilling may reveal less resource than is currently estimated, especially in the categories of mines that are less geologically certain."

"Additional concerns include the possibility that the stability of future primary uranium supplies will decrease. More primary uranium will be supplied from Kazakhstan, Africa (Namibia, Niger), Australia, and Canada, with production from other countries remaining flat. Production in Australia is tied to the large Olympic Dam deposit, and Canada largely depends on the development of the Cigar Lake and the Midwest mines. The dependence of uranium supply on large individual uranium properties and countries adds uncertainty to estimates of future supply. Major producers Cameco, Areva, KazAtomProm, Rio Tinto, ARMZ/Uranium One, and BHP Billiton are expected to continue to maintain their large market share into the future."

A methodologically different approach than the publications above was chosen by **Michael Dittmar (2011)**. He evaluated the past mining histories, resources and amounts of extraction and applied those for future uranium mining:

"Using this model for all larger existing and planned uranium mines up to 2030, a global uranium mining peak of at most 58±4 ktons around the year 2015 is obtained. Thereafter we predict that uranium mine production will decline to at most 54±5 ktons by 2025 and, with the decline steepening, to at most 41± 5 ktons around 2030. This amount will not be sufficient to fuel the existing and planned nuclear power plants during the next 10-20 years. In fact, we find that it will be difficult to avoid supply shortages even under a slow 1%/year worldwide nuclear energy phase-out scenario up to 2025. We thus suggest that a worldwide nuclear energy phase-out is in order."

"If such a slow global phase-out is not voluntarily effected, the end of the present cheap Uranium supply situation will be unavoidable. The result will be that some countries will simply be unable to afford sufficient uranium fuel at that point, which implies involuntary and perhaps chaotic nuclear phase-outs in those countries involving brownouts, blackouts, and worse."

In 2011 a **diffusion model** was applied on global uranium mining at the **University of Padua**, Italy to estimate the future of uranium extraction (Guidolin and Guseo, 2011). The authors conclude, that:

"Despite a recent increase, probably due to the Kazakhstan boom, the global pro-duction of uranium seems to be doomed to decline severely in the next twenty years, in accordance with the predictions of the Energy Watch Group [7]. The choice to model uranium production data to provide an indirect estimate of reserves seems particularly reasonable, considering the quite unreliable information provided on reserves, for instance in the Red Book. We foresee a declining pattern for reactor startups as well; although there are 60 reactors under construction in China, Russia, and India, giving evidence to the aggressive energy policy of these countries, it may be useful to remind that not even the 50% of similar past nuclear growth scenar-ios in the OECD block were eventually realized."

4 ALTERNATIVE TECHNOLOGIES AND FUEL CYCLES

Over the past years the expectations on nuclear growth and the finiteness of uranium-235, once again drew the focus of nuclear R&D towards alternative fuel cycles.

The concept behind alternative fuel cycles is to convert ("breed") an otherwise non – fissile isotope –to a fissile isotope, which then is burned in a reactor. This is feasible for uranium-238 by breeding plutonium-239 or thorium-232 by breeding uranium-233. As almost all of the uranium is the isotope uranium-238 (99.3%) and even more of the thorium is thorium-232, this would substantially increase the amount of fissile material available, compared to the 0.7% fraction of uranium-235 currently burned in reactors.

The concept of a thorium based reactor is expected to have some advantages such as better proliferation resistance[32], operating in a thermal neutron spectrum and generation of less waste (IAEA, 2010: p.1). This was already assumed in the early days of nuclear energy. In the past 50 years several countries have operated experimental thorium reactors (IAEA, 2005: p.4). No reactor based on thorium has reached commercial scale so far. Currently there are several thorium reactor concepts under consideration once again. Due to the long lead times from feasibility to commercial operation (see EHNUR Workpackage 4) <u>thorium breeders cannot be expected to influence uranium supply for at least the next two decades</u>, especially as only a few prototypes can be expected to be in operation sometime after 2020.

<u>The very same can be applied for uranium breeder reactors</u>. A few fast breeder reactors have been operated on experimental or demonstration scale in the past, with three currently in operation (WNA, 2013f). The only commercial scale breeder – Superphénix – operated with little success until 1997 (Wikipedia, 2013c). Currently there are two fast reactors under construction, and eight reactors planned, which could go into operation between 2020 and 2030.

Nonetheless thorium resources are presented hereafter, so they can be put in relation to available uranium resources.

4.1 THORIUM RESOURCES

Thorium is a naturally occurring radioactive metal. It is about 4 times as abundant in earth's crust as uranium (6 ppm vs. 1.4 ppm).Thorium resources have mostly been discovered during exploration of uranium, rear earth elements and other metals. They were evaluated in the IAEA Redbooks alongside Uranium resources starting the 1960s (OECD-NEA / IAEA, 2006a). It was considered as a relevant fuel for high temperature reactors, operating in a thorium fuel cycle parallel to the uranium cycle. Thorium resource figures were then regularly published until the 1980s based on a similar classification system as for uranium using classes of recovery costs and confidentiality, also called

[32] Note that the proliferation resistance of thorium is currently under discussion, as "*simple chemical pathways open up proliferation possibilities for the proposed nuclear 'wonder fuel'*" (Ashley et al., 2012).

Reasonably Assured Resources and Estimated Additional Resources (now called Inferred Resources). At this point in time it was already clear, that there was now commercial interest in a thorium cycle. Thus also updating of thorium resource numbers was of no interest and neglected in the two decades to come.

With the perspective of an increased future nuclear share in the past years also the interest in thorium rose again. In 2007 a separate chapter on thorium was introduced once again in the Uranium Redbook (OECD-NEA / IAEA, 2008), which was carried on to the Redbook 2009. The numbers on thorium resources still originated from the 1980s. A total of 6.1 million tons of Th were estimated. In the cost category of <USD 80/kg Th about 800,000 tons of RAR and 2.2 million tons of Identified resources were presented.

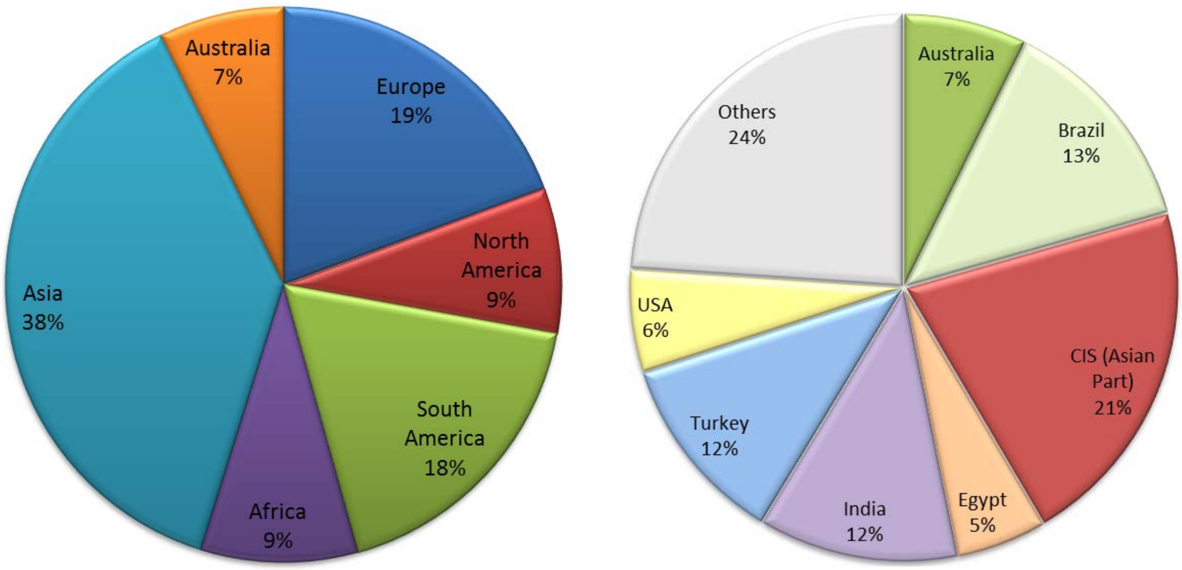

FIGURE 63: GLOBAL DISTRIBUTION OF THORIUM RESOURCES[33] DATA:(OECD-NEA / IAEA, 2012)

In 2011 an international meeting on "World Thorium Resources" was held in India, to finally get an update on thorium resource figures. After this meeting the total resources could be evaluated to a range from 6,730,000 to 7,590,800 t Th. This amount does not account for cost of confidence categories. Figure 63 shows the distribution of these resources by continent and the countries with the largest resources. The overall amount for the Asian part of the CIS countries was estimated to be 1.5 million tons. India and Turkey both are expected to account for about 800,000 t Th. The resources of Brazil are stated in a large range of uncertainty, between 606,000 and 1,300,000 t Th.

In response on the increased interest on thorium, the IAEA furthermore started developing the "World thorium deposits and resources" database ThDEPO (IAEA, 2013), which is similar to the

[33] The average value of the resource ranges was chosen to crate the figures. 7.2 million t Th in total.

uranium database UDEPO. It contains almost 1000 entries (deposits) from 26 countries at the moment, but mostly the resource data is “unknown”.

The most promising way of recovering thorium in the near future is expected to be monazite (Ce-La-Y-phosphate mineral containing 8-10% of Th), as thorium can be recovered as a by-product to rare earth elements (REE). Based on India’s monazite production – which was 90% of global production or about 6000 tU in the early 2000s- between 300 and 600 tTh could be recovered(OECD-NEA / IAEA, 2006a). This could provide fuel for 30 – 60 GWe of nuclear power (Barthel, 2005), not accounting for the higher startup loads of Th and the initial highly enriched uranium needed (10 tons per GWe).

5 DISCUSSION/CONCLUSIONS

This report deals with a variety of issues that affect the current and future aspects of nuclear fuel supply. While the public debate often revolves around the amount of resources available, it became quite obvious that not only this alone will impact the future supply of nuclear power plants. Based on expansion plans for nuclear energy, it is clear, that uranium-235 will stay the main fuel for at least the next few decades. Other fuel cycles currently fail primarily in the technical implementation and thus an extensive expansion of alternative fission technologies is not in sight.

Today's reactor park is supplied with uranium from primary sources (the direct mining production) and secondary sources (the reprocessing of spent fuel and the contribution due to downblending of weapons-grade uranium). Since the secondary sources are limited in quantity and other, unconventional sources of uranium appear financially - and probably energetically - unprofitable, it can be assumed that the future fuel supply must be covered by primary uranium.

An analysis of the current market situation shows that the uranium is provided by a few countries only. Kazakhstan has the largest share with nearly 40% of global uranium production, Kazakhstan, Canada and Australia together have about 70% share. Other major countries in uranium production are Niger, Namibia, Russia and – to a limited extent – Uzbekistan and the United States. It is striking that the producing countries are different from the uranium consumers. Worldwide only two countries (Canada and South Africa) that operate nuclear power plants meet their uranium requirements from own production. The biggest consumers, the EU and the U.S., could cover only 2.5% and 8% from own production respectively in 2012.

As the largest producers are also the same as those with the greatest resources, it can be assumed that they will also dominate the market in the future. This is also reflected in the production scenarios generated for this report, which are substantially shaped by the development of a few countries and production centers[34].

Kazakhstan has shown a strong growth in production in recent years, being the only country contributing to close the gap between supply and demand and thus reducing the dependence on secondary resources. However, Kazakhstan will reach peak production in a few years. The growth rates have been in the single digit range the last two years and the initial target to produce 30,000 tons a year by 2015 seems out of reach. Based on the Kazakh resource assessment, the production growth will eventually be followed by a steep decline due to the depletion of the now operating mines. This raises the need for development of compensatory production by others, which might be hindered or delayed through Kazakhstan's currently high production itself.

For **Australia**, as the country with the largest resources, it was shown, that due to a limited possibility for capacity expansion, large resources rather provide a long term baseline production, than a peak supply of uranium, as the resources cannot be recovered in a reasonable timespan. An

[34] See details on the countries in Annex II.

expansion of production at the Olympic Dam mine has a large influence on of the production scenarios. Such an expansion, making it the largest uranium producing facility, was planned two years ago (World Nuclear News, 2011). The project was cancelled in the year 2012 (World Nuclear News, 2012), so the output will stay at about 4000 tU/yr at least for the next 5 – 10 years.

The future of uranium mining in other countries is mainly dependent on few large mines and projects. These are McArthur River and Cigar Lake for **Canada**, Imouraren for **Niger**, Husab for **Namibia** and the Elkon deposit for **Russia**.

Our **Scenarios** for the future uranium supply reveal several challenges for the supply of uranium-235. As a first result delays of startups could be reflected by the choice of different reference dates. The scenarios show a slower growth of the global production for the more recent data (2012) than for scenarios created with the 2009 data set. A shift of the production peak further into the future can be observed. This confirms the assumption that the scenarios reflect rather optimistic growth rates in production and that delays in the uranium industry are quite common.

All of the scenarios for **Reasonably Assured Resources** stay below a maximum output of 90,000 tU per year, peaking between 2020 and 2030. Based on these resources a growth of nuclear power using ^{235}U doesn't seem viable, all the more as mining of all the resources is taken for granted for the scenarios. These scenarios are sensitive to the development of the large mines mentioned before. Since the different scenarios depend on the success of the currently planned mining projects, it appears quite possible that an unfavorable development can result in supply shortages or significant price increases already around 2020.

The most optimistic scenario of **Identified Resources** could support some intermediate growth of nuclear energy and provide up to 110,000 tU annually until 2060, which corresponds to the fuel for about 600 – 650 GWe of LWRs. It assumes all of the resources can be mined, life-time extensions of existing mines and no delays in plans. Thus the RAR scenarios seem more realistic. It has to be noted, that in none of the scenarios a high demand scenario of the IAEA can be met after 2030.

As the cost of fuel has a rather low share in the nuclear energy generating costs, also higher uranium prices (above 260 USD/kgU) would still be affordable by NPP operators. Thus increased prices could result in some additional resources being economically mineable. Still, such additional resources cannot be expected to have a major impact on the supply situation of the coming two decades. Mining of such resources could occur, when the currently operating mines and known deposits are depleted.

Some aspects affect all uranium mining activities, such as the long lead times for development of new mines. Therefore an early concept of succession planning is necessary to ensure medium term security of supply. At this point, the short-term economic view of the companies operating uranium production facilities stands in contrast to the long-term aspects of nuclear energy. It cannot be expected, that a uranium producer starts the development of a uranium deposit now, to secure the supply of an operator in ten or fifteen years, if the current market conditions do not permit this.

Furthermore it was noted, that concerning the quality of the uranium ore it can be assumed, that the best ore has already been extracted in the past, so production efficiency and economic competiveness can be expected to decline in the future. Problems in technical implementation, political restrictions and socio-economic conflicts are likely to influence the future nuclear energy market the most and contain major uncertainties, but they are quantitatively hard to measure.

Concerning unconventional resources, the extraction of uranium from seawater is likely to remain insignificant, since it would be very expensive and associated with high technical and energy expenditure due to the low concentration of uranium. The separation of uranium from phosphate ores is primarily discussed as the phosphate content of fertilizers has increased in recent years. The technology of uranium separation is proven, but very expensive. Therefore, the separation of uranium will be determined primarily by the phosphate requirements. The maximum recovery rates were recently evaluated to 11,000 tons per year (about 15% of the current annual demand). Nonetheless not more than of 3,000 to 5,000 tons (5-7%)are expected in the short and medium term.

As for reprocessing of fuel it can be stated, that it is limited in capacity. The construction of new reprocessing plants comes with political and social reservations, as well as long lead times because the technology is difficult to control. The separated uranium is contaminated with unwanted isotopes, so use in reactors is limited. In sum, the contributions from reprocessing may amount to a few thousand tons of uranium in the coming years.

Alternative fuel cycles cannot substitute uranium in the coming decades. Too many technical issues must be solved while only few pilot and demonstration plants are planned. A related commercial fuel cycle is thus far in the future.

Other publications and analyses provide us with similar insights. Independent scientific publications expect peak productions between 58,000±4,000 tU and 115,000 tU around 2020. The uranium industry itself projects a decline in uranium production after 2020, which stands in contrast to the expected rising demand. The peaks in supply for this year are expected between 60,000 tU and 95,000 tU (110,000 tU including secondary resources).

In a nutshell it can be stated that the nuclear industry does not only face challenges in the overall long term availability of uranium resources, but the short and medium-term challenges to provide sufficient uranium for the envisaged growth in global nuclear capacity.

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ANNEX I: REPORTS AND SOURCES USED FOR THE DATABASE

Areva, Paris, France.

Annual Report 2002
Annual Report 2003
Annual Report 2004
Annual Report 2005
Annual Report 2006
Annual Report 2007
2008 Reference document
2009 Reference document
2010 Reference Document
2011 Reference Document
2012 Reference Document

Atomredmetzoloto (ARMZ), Moscow, Russia.

Annual Report 2009
Annual Report 2010
Annual Report 2011

BHP Billiton, Melbourne, Australia.

Annual Report 2001
Annual Report 2002
Annual Report 2003
Annual Report 2004
Annual Report 2005
Annual Report 2006
Annual Report 2007
Annual Report 2008
Annual Report 2009
Annual Report 2010
Annual Report 2011
Annual Report 2012

Cameco, Saskatoon, Canada.

Annual Information Form 1995
Annual Information Form 1996
Annual Information Form 1997
Annual Information Form 1998
Annual Information Form 1999
Annual Information Form 2000
Annual Information Form 2001
Annual Information Form 2002
Annual Information Form 2003
Annual Information Form 2004
Annual Information Form 2005
Annual Information Form 2006
Annual Information Form 2007
Annual Information Form 2008

Annual Information Form 2009.
2010 Annual Report.
2011 Annual Report.
2012 Annual Report.

Energy Resources of Australia Ltd (ERA), Darwin, Australia

2000 Annual Report
2001 Annual Report
2002 Annual Report
2003 Annual Report
2004 Annual Report
2005 Annual Report
2006 Annual Report
2007 Annual Report
2008 Annual Report
2009 Annual Report
2010 Annual Report
2011 Annual Report
2012 Annual Report

Paladin Energy Ltd, Perth, Australia

2008 Annual Report
2009 Annual Report
2010 Annual Report
2011 Annual Report
2012 Annual Report

Rio Tinto, London, UK and Melbourne, Australia

Annual Report 2003
Annual Report 2004
Annual Report 2005
Annual Report 2006
Annual Report 2007
Annual Report 2008
Annual Report 2009
Annual Report 2010
Annual Report 2011

Uranium One (Southern Cross Resources until 2005), Toronto, Canada.

Annual Report 1997
Annual Report 1998
Annual Report 1999
Annual Report 2000
Annual Report 2001
Annual Report 2002
Annual Report 2003
Annual Report 2004
Annual Information Form 2005
Annual Information Form 2006

Annual Information Form 2007
Annual Information Form 2008
Management's discussion and analysis 2009.
Annual Report 2010
Annual Report 2011
Annual Report 2012

IAEA, Uranium Redbook editions, Paris, France

Uranium 1970: Resources, Production and Demand
Uranium 1977: Resources, Production and Demand
Uranium 1983: Resources, Production and Demand
Uranium 1989: Resources, Production and Demand
Uranium 1995: Resources, Production and Demand
Uranium 1999: Resources, Production and Demand
Uranium 2001: Resources, Production and Demand
Uranium 2003: Resources, Production and Demand
Uranium 2005: Resources, Production and Demand
Uranium 2007: Resources, Production and Demand
Uranium 2009: Resources, Production and Demand
Uranium 2011: Resources, Production and Demand

Deffeyes, K.S., MacGregor, I.D., 2001. World Uranium Resources. Sci. Am. 242, 66–76.

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OECD-NEA / IAEA, 2006. Forty years of uranium resources, production and demand in perspective: "the Red Book retrospective.", Nuclear development. Nuclear Energy Agency, Organisation for Economic Co-operation and Development, Paris, France.

Web resources and online databases

INFOMINE - http://www.infomine.com/

WISE Uranium - http://www.wise-uranium.org/

World Nuclear Association (WNA) - http://www.world-nuclear.org/

IAEA. UDEPO - World distribution of Uranium deposits. http://infcis.iaea.org/UDEPO/About.cshtml

Kazatomprom - ISL mines. http://www.kazatomprom.kz/15000/?f5&&version=en (accessed 5.1.08).

UIC - Australia's Uranium Deposits and Prospective Mines, http://www.uic.com.au/pmine.htm (accessed 27.7.08)

UIC - Australia's Uranium Mines, http://www.uic.com.au/emine.htm (accessed 28.7.08)

United Nations Commodity Trade Statistics Database - http://comtrade.un.org

ANNEX II: KEY COUNTRIES

Based on resources and production figures Australia, Canada, Kazakhstan, Niger, Nigeria and Russia can be considered as the key countries of uranium production. Additionally Brazil, South Africa and the USA all account for more than 4% of global identified resources, but show rather low production quantities over the past years.

AUSTRALIA

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity	Production 2012 [tU]
1 180 100	1 738 800	0.04	3	9 308	6 990

In the late sixties and seventies a large exploration wave took place in Australia to provide uranium for a rising nuclear energy sector. During this time, most of the approximately 100 known deposits were discovered. The deposits are spread across the continent and are subject to the political influence of the territorial governments on the one hand and the indigenous population on the other. Thus, it often is for the benevolence of a tribe, whether uranium can be mined or not.

Today Australia is the country with the most Reasonably Assured and Identified Resources, amounting to 1.2 million and 1.75 million tons in the highest cost category (260 $/kg). Uranium is produced at the Olympic Dam, Ranger and Beverley production centers, and a pilot plant at the Honeymoon deposit.

A peculiarity of the Australian resources is that more than 75% - at the same time 20% of the global resources – are located in one deposit, the Olympic Dam deposit. At this deposit uranium occurs together with copper, gold and silver and is mined as a by-product. From a risk perspective, having large amounts of resources located at one deposit only, has the downside, that flexibility is constricted and risk for the security of supply are created.

FIGURE A-1: AREAL VIEW OF THE OLYMPIC DAM MINE

For the past years an expansion of the mining output to 16,000 tU was planned, making it the largest uranium producing facility (World Nuclear News, 2011). The project was cancelled in the year 2012 (World Nuclear News, 2012), so the output will stay at about 4000 t pa at least for the next 5 – 10 years.

Additionally it would take about one century to extract all of the uranium from the Olympic Dam deposit, even if production continues to be on such a very high level. The other Australian mines would only contribute with comparatively small portions to the countries uranium export.

Thus Australia could rather provide a long term, though high supply baseline, but associated with elevated risks for security of supply.

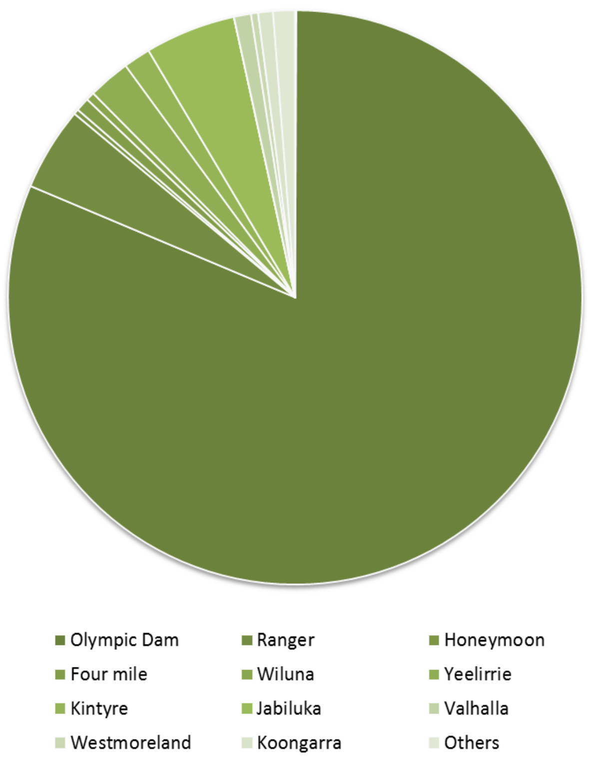

FIGURE A-2: DISTRIBUTION OF RAR - AUSTRALIA

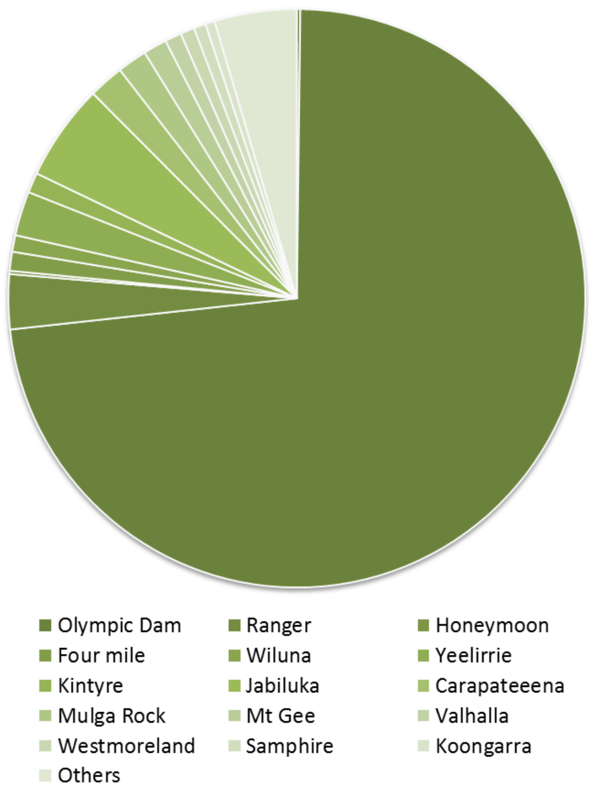

FIGURE A-3: DISTRIBUTION OF IR - AUSTRALIA

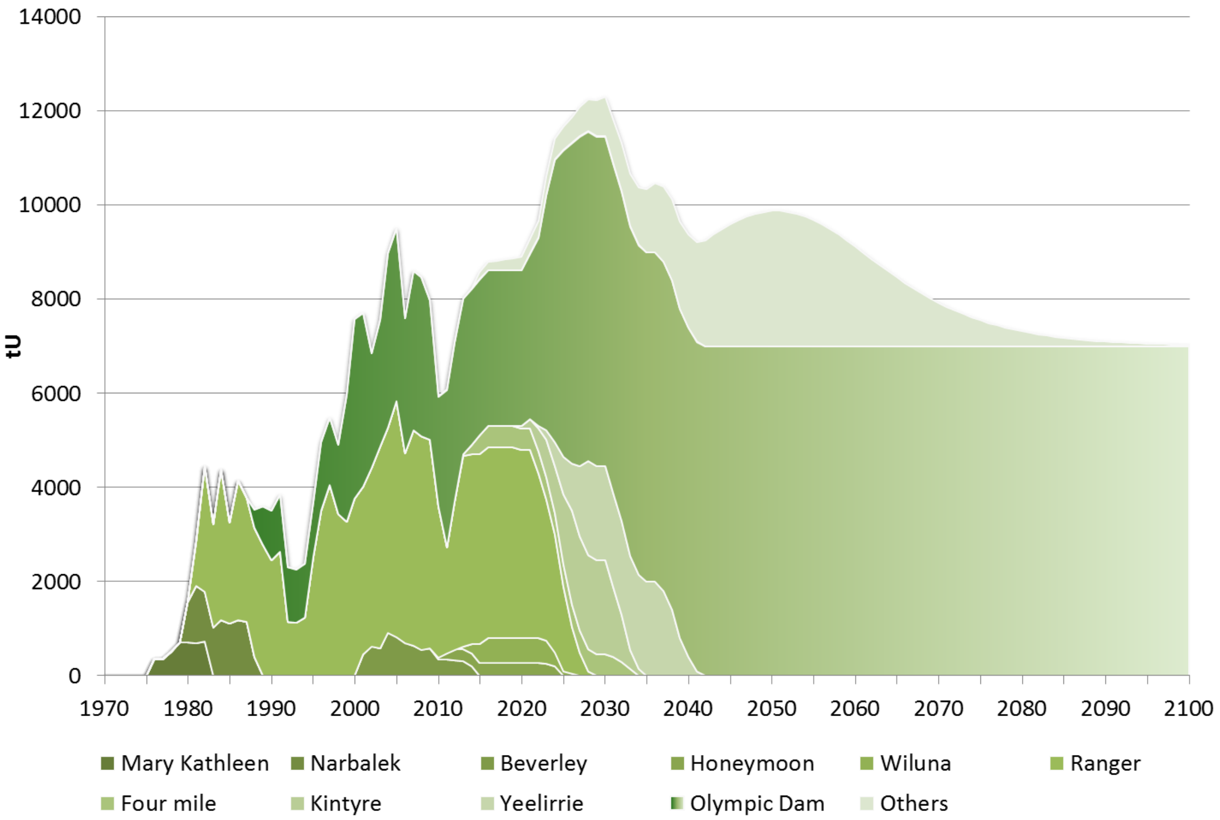

FIGURE A-4: AUSTRALIAN PRODUCTION SCENARIO BASED ON REASONABLY ASSURED RESOURCES, OLYMPIC DAM EXPANSION TO 9000 T P.A., 80% CAPACITY LOAD – RAR 1

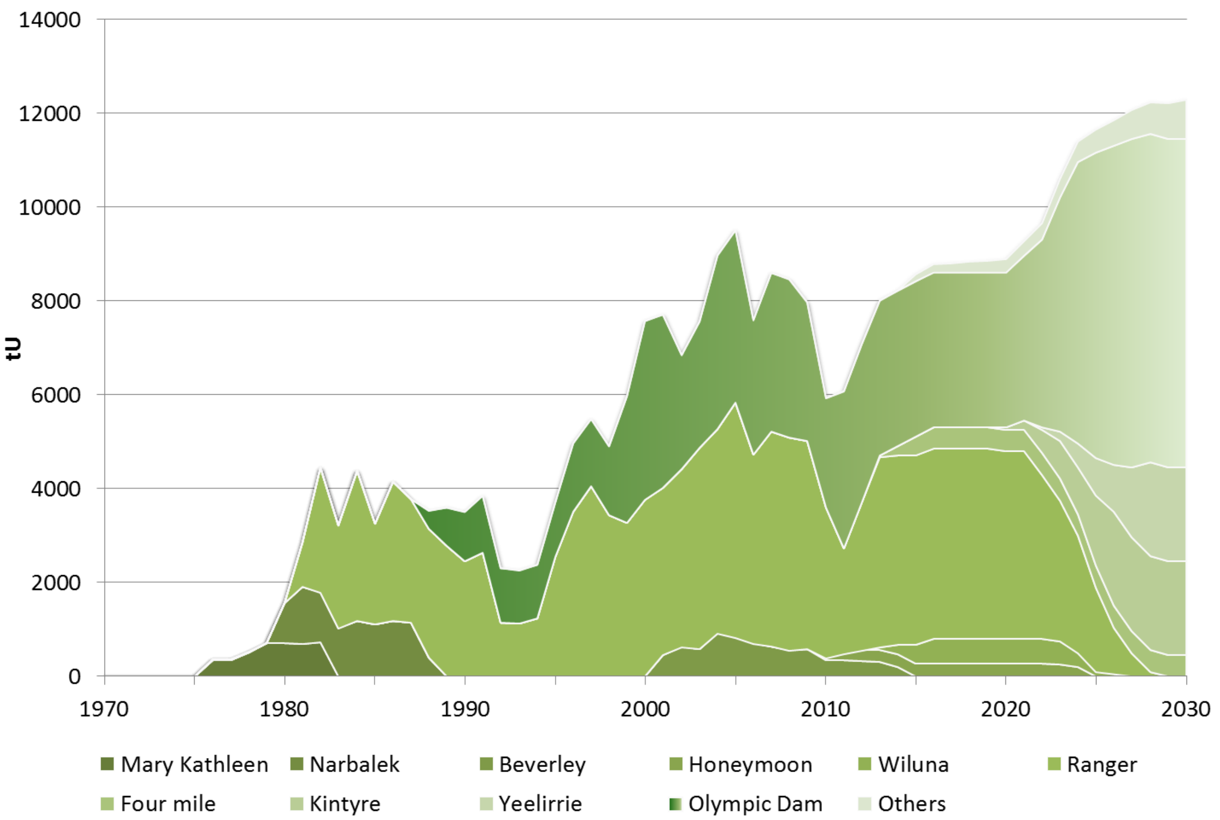

FIGURE A-5: AUSTRALIAN PRODUCTION SCENARIO – RAR 1 SHORT

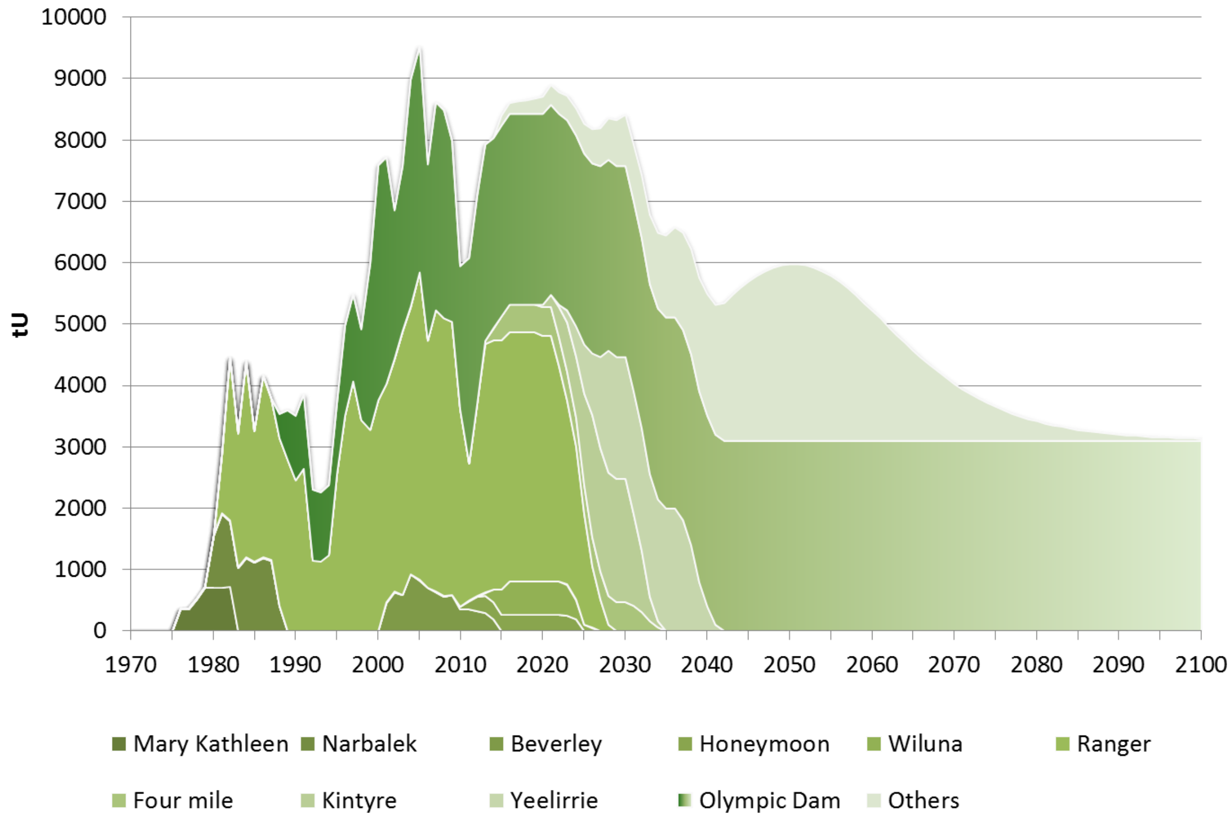

FIGURE A-6: AUSTRALIAN PRODUCTION SCENARIO, NO OLYMPIC DAM EXPANSION – RAR 2

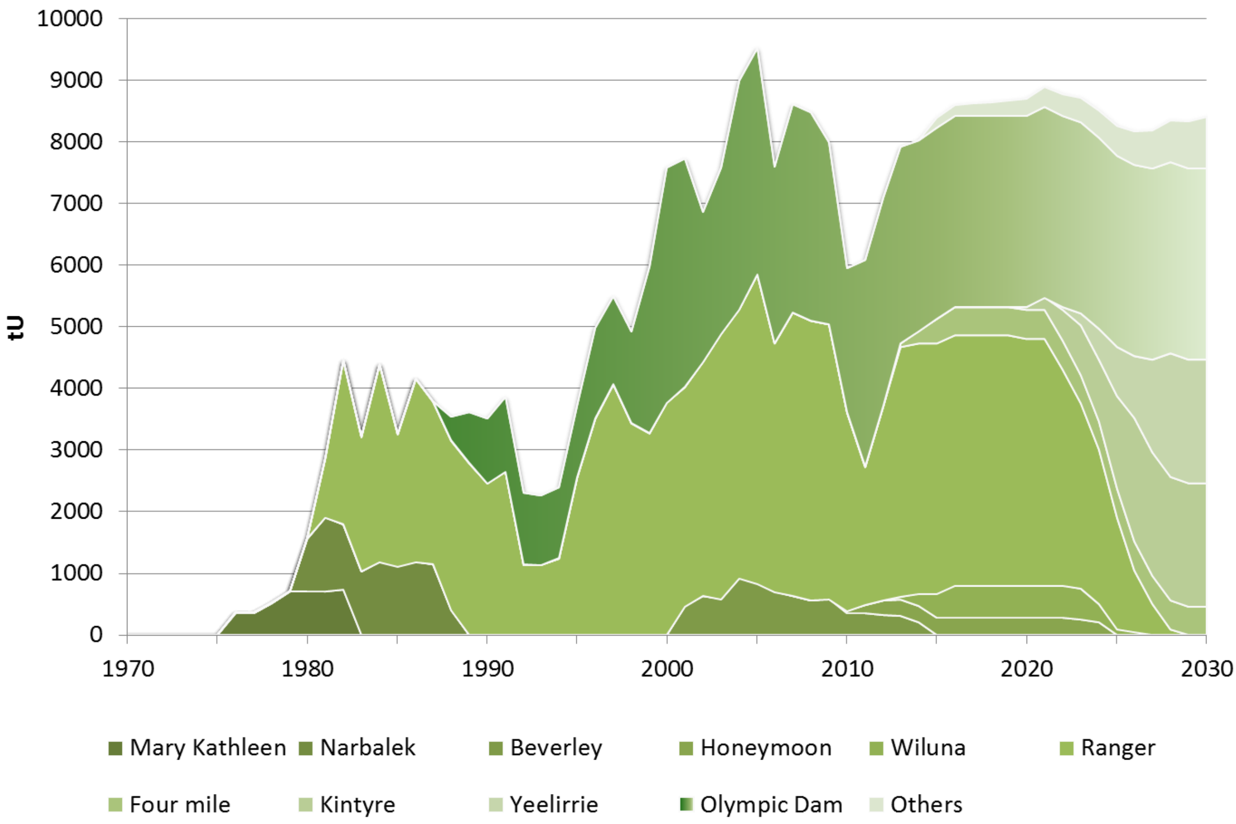

FIGURE A-7: AUSTRALIAN PRODUCTION SCENARIO – RAR 2SHORT

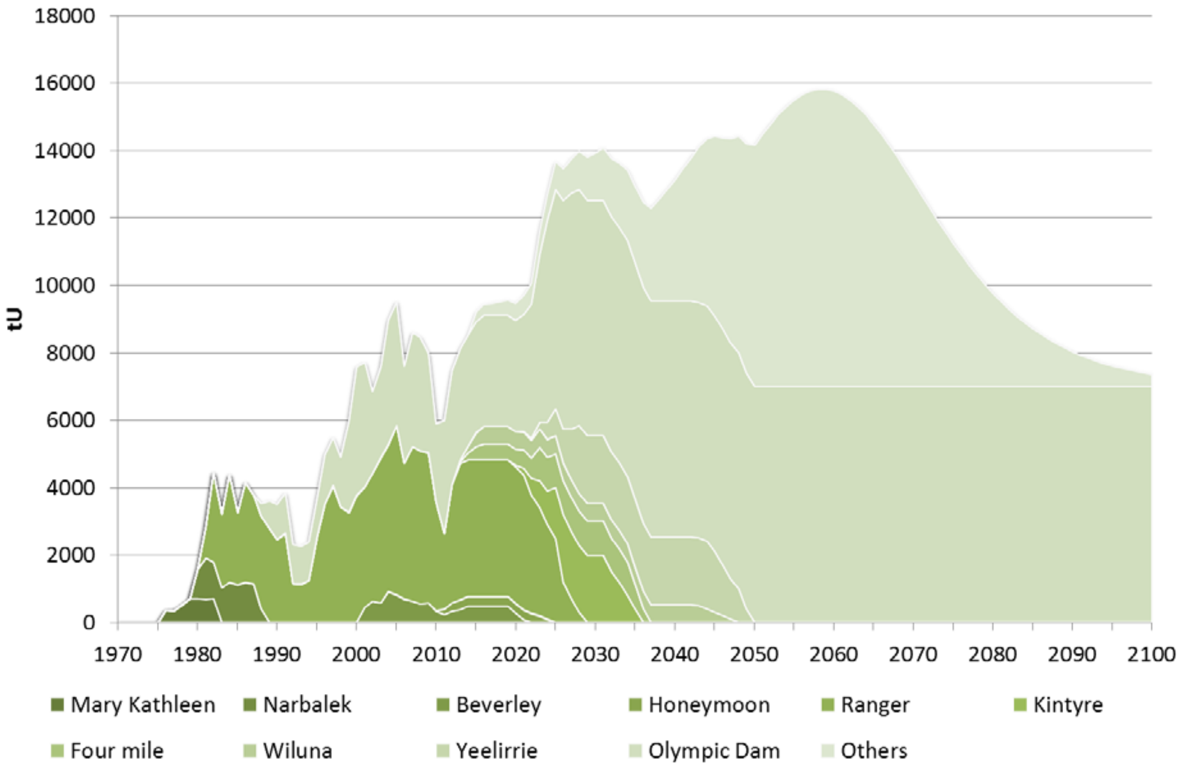

FIGURE A-8: AUSTRALIAN PRODUCTION SCENARIO, OLYMPIC DAM EXPANSION – IR 1

CANADA

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity	Production 2012 [tU]
421 900	614 400	10.6	2	12465	8990

Canada is one of the leading uranium producers for some decades now and is the location of the currently largest uranium mine McArthur River. Canadian uranium mining is concentrated in the Athabasca Basin of northern Saskatchewan. Other provinces are showing resentment against the uranium industry, mainly due to increased exploration activity. The future development of the countries uranium output depends on McArthur River and the Cigar Lake Project. The latter is under construction since 2005, but commissioning has been postponed repeatedly due to water ingress and is currently being sought for the end of 2013. The total capacity of these two mines would be about 14,000 tU per year.

In 2012 Canada provided 15% of world production.

The Canadian production scenarios show that most of the country's RAR can be expected to deplete in 15 years, the IR 10 years later.

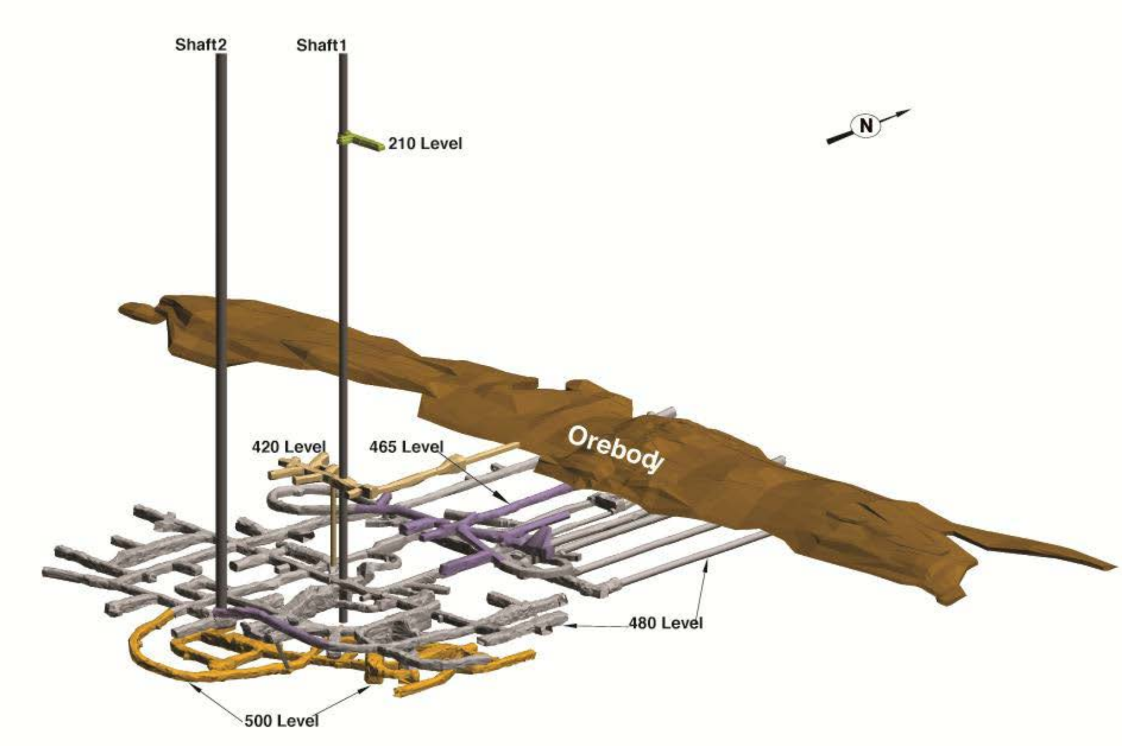

FIGURE A-9: CIGAR LAKE MINERALISATION © CAMECO (CAMECO, 2013)

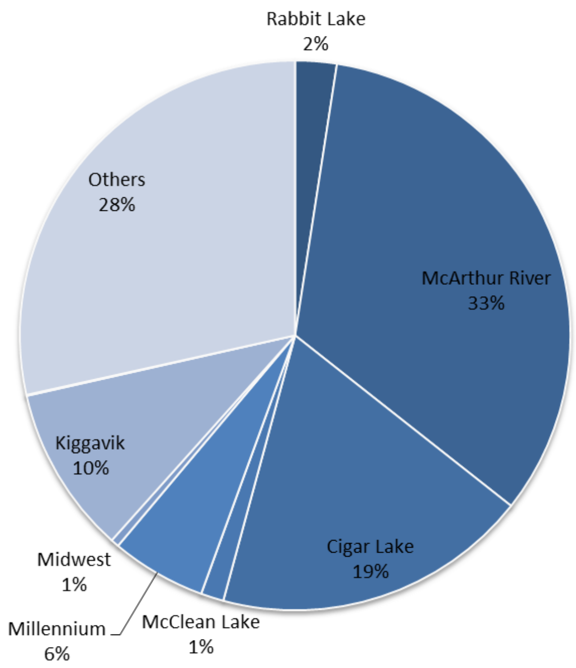

FIGURE A-10: DISTRIBUTION OF RAR - CANADA

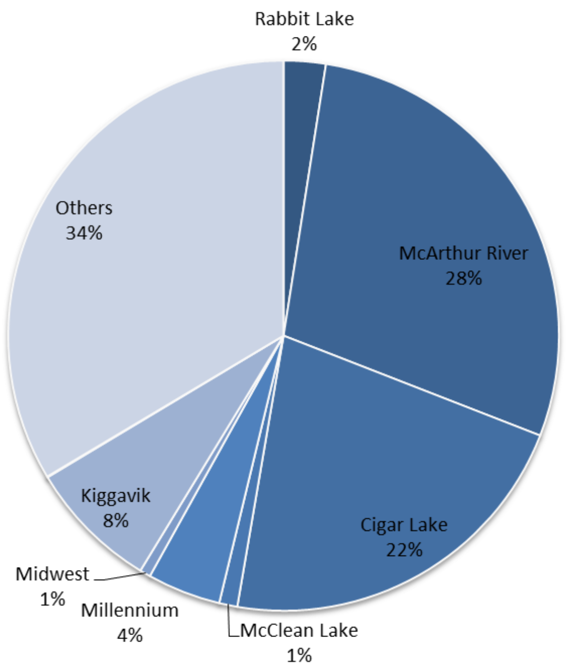

FIGURE A-11:: DISTRIBUTION OF IR - CANADA

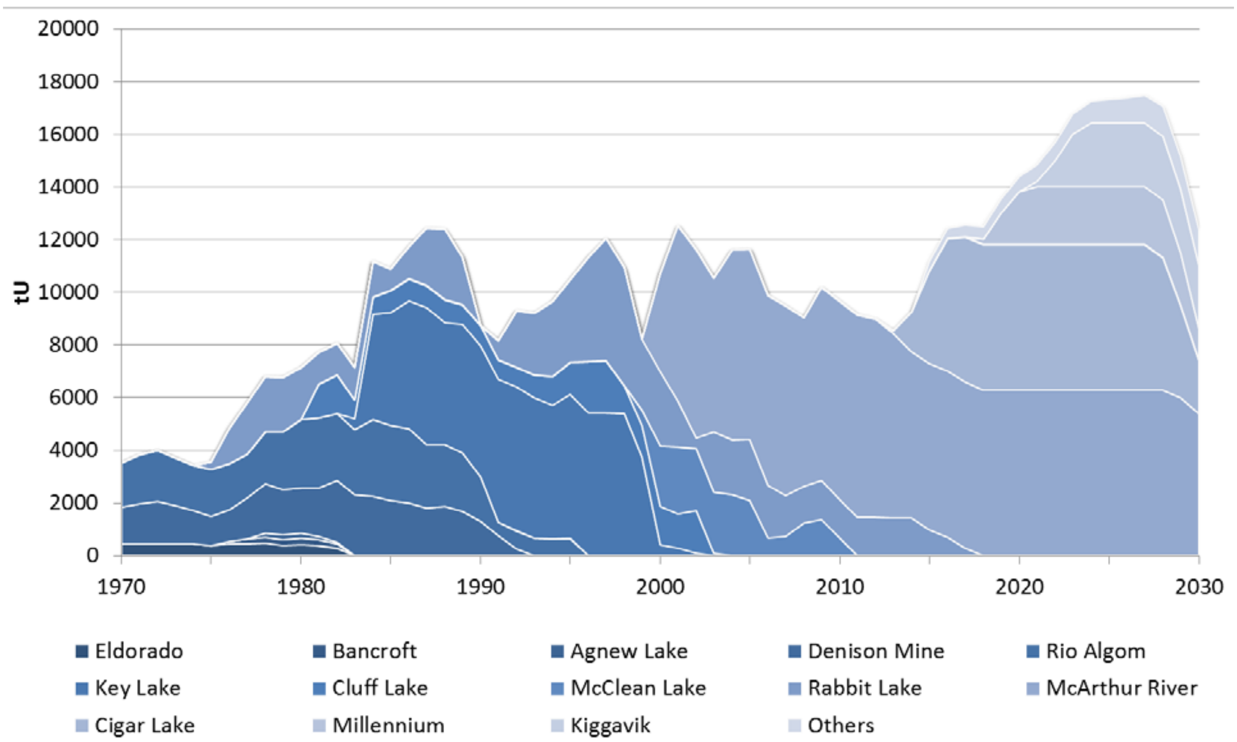

FIGURE A-12: CANADIAN PRODUCTION SCENARIO – RAR 1 SHORT

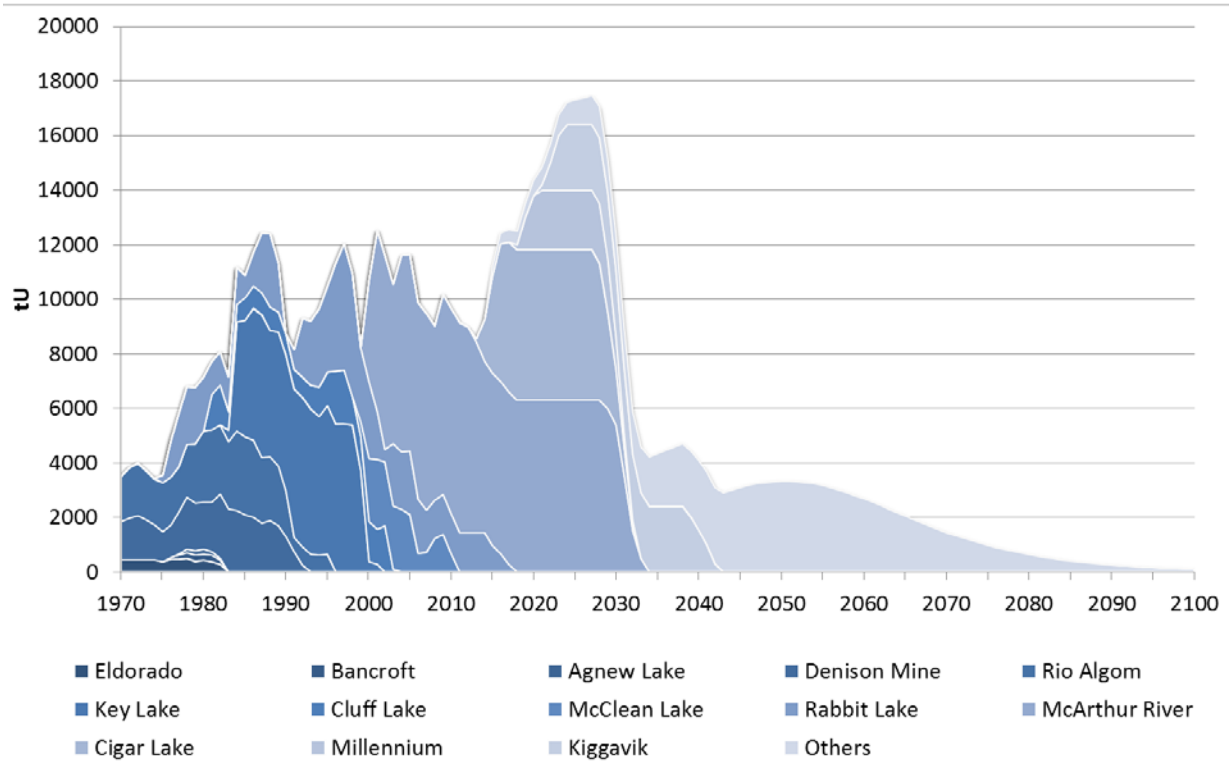

FIGURE A-13: CANADIAN PRODUCTION SCENARIO – RAR 1

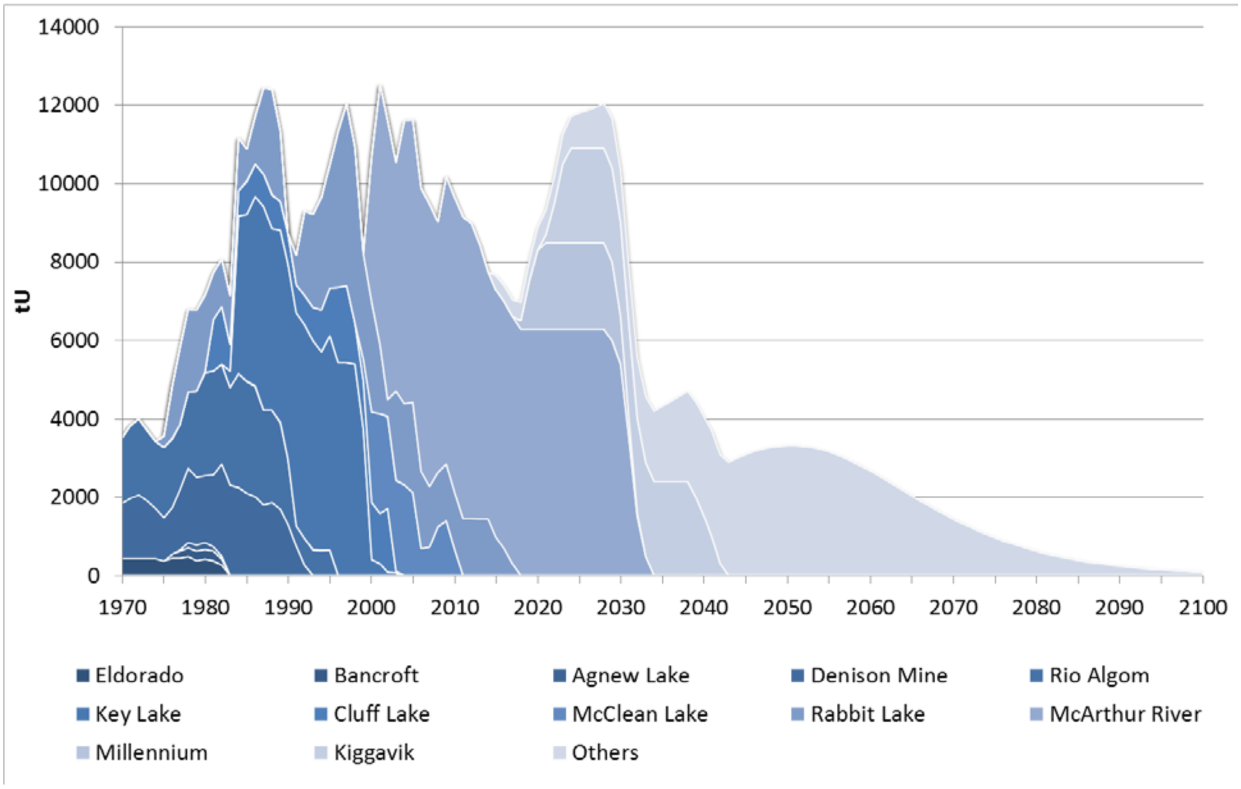

FIGURE A-14: CANADIAN PRODUCTION SCENARIO, NO CIGAR LAKE – RAR 1

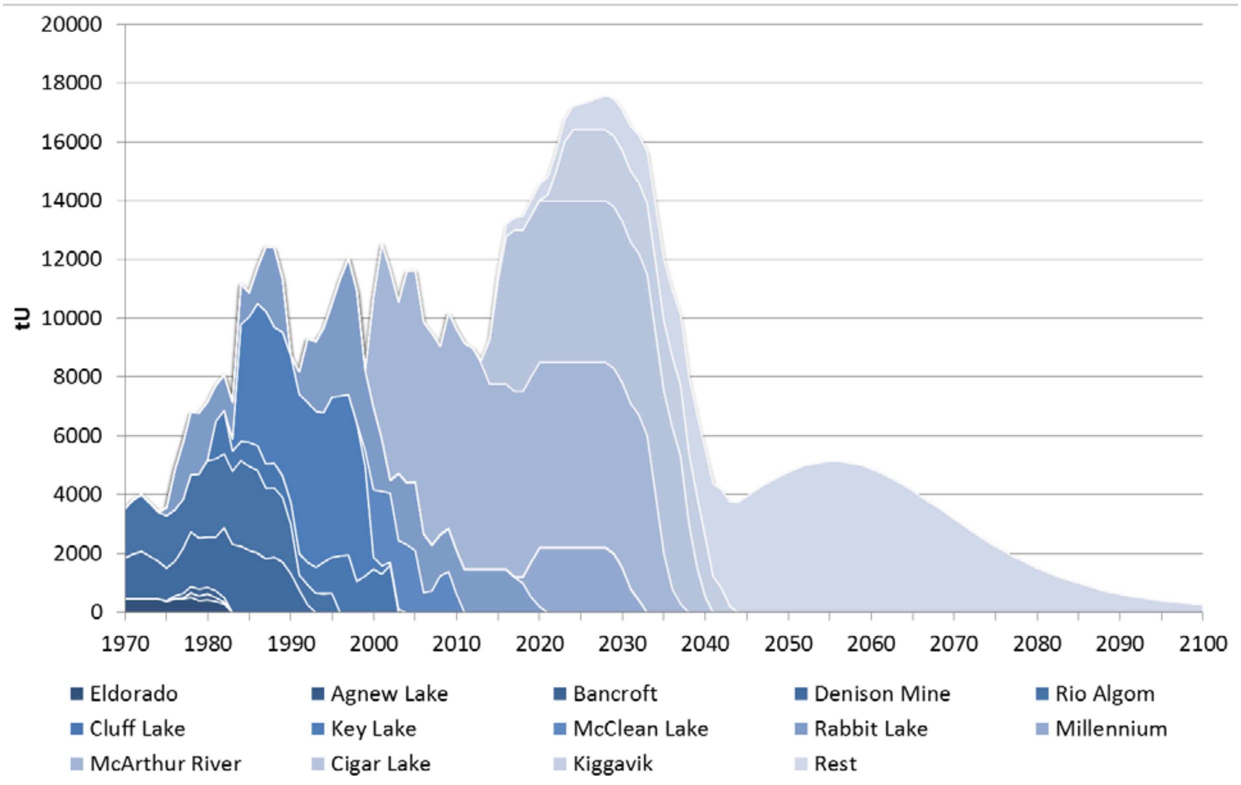

FIGURE A-15: CANADIAN PRODUCTION SCENARIO – IR 1

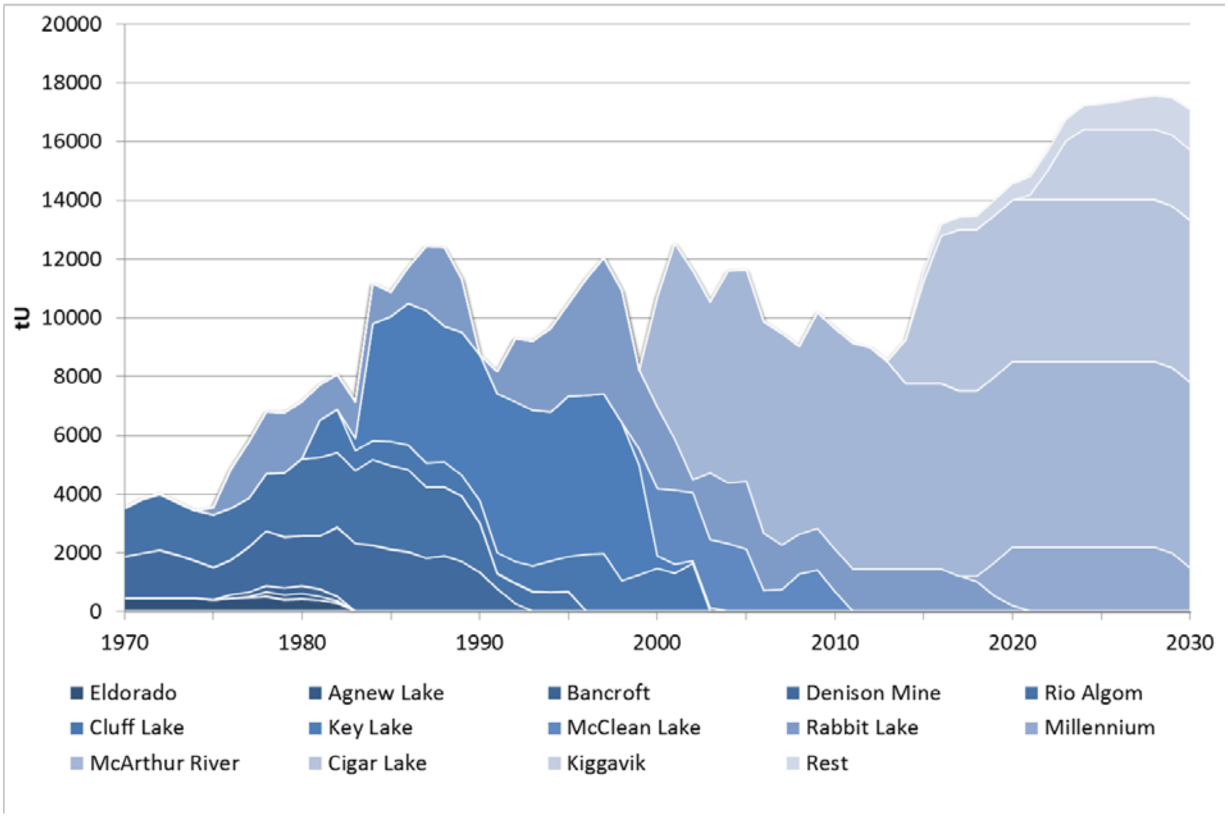

FIGURE A-16: CANADIAN PRODUCTION SCENARIO – IR 1 SHORT

KAZAKHSTAN

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity	Production 2012 [tU]
402 400	819 700	0.06	18	27 190	21 000

Kazakhstan has a long history as a producer of uranium. In 1957 the first mine was put into operation. All uranium exploration and mining activities in the country are in the hands of the state company Kazatomprom, but with some participation of Western companies. An insight into the uranium-related activities of the Central Asian state therefore is more and more possible. In the early 2000s Kazatomprom has launched an ambitious plan to produce 15,000 tons by 2010 to and to 30000 t U in a next step by 2015. As a consequence the production could be increased tenfold from 2000 to 2010. The production in 2010 (18,000 t U) even outnumbered the very ambitious development plan (Figure A-18). On the other hand, looking at the upcoming projects and the growth rates of the last two years, it seems probable, that the further target, to reach a production of 30,000 tons, will not be reached (Figure 11).

One of the most important findings from the production scenarios is, that the large growth in output is followed in rapid decline. Before the production starts to decline between 2015 and 2020, substituting mines have to be put in place in a timely manner. As this seems not possible based on the country's resources, the Kazakh decline in production would have to be covered by other countries or secondary resources.

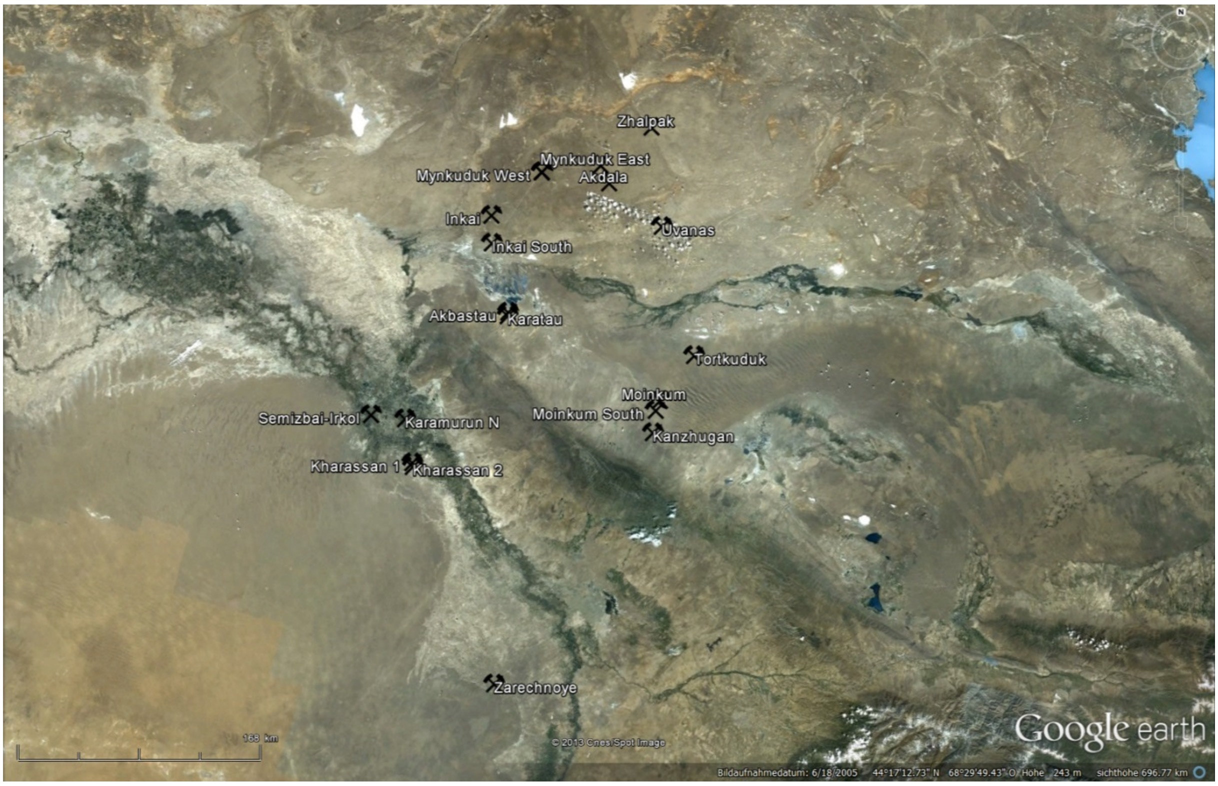

FIGURE A-17: SATELLITE VIEW OF SOUTHERN KAZAKSTAN AND URANIUM MINES (GOOGLE EARTH, ©GOOGLE INC.)

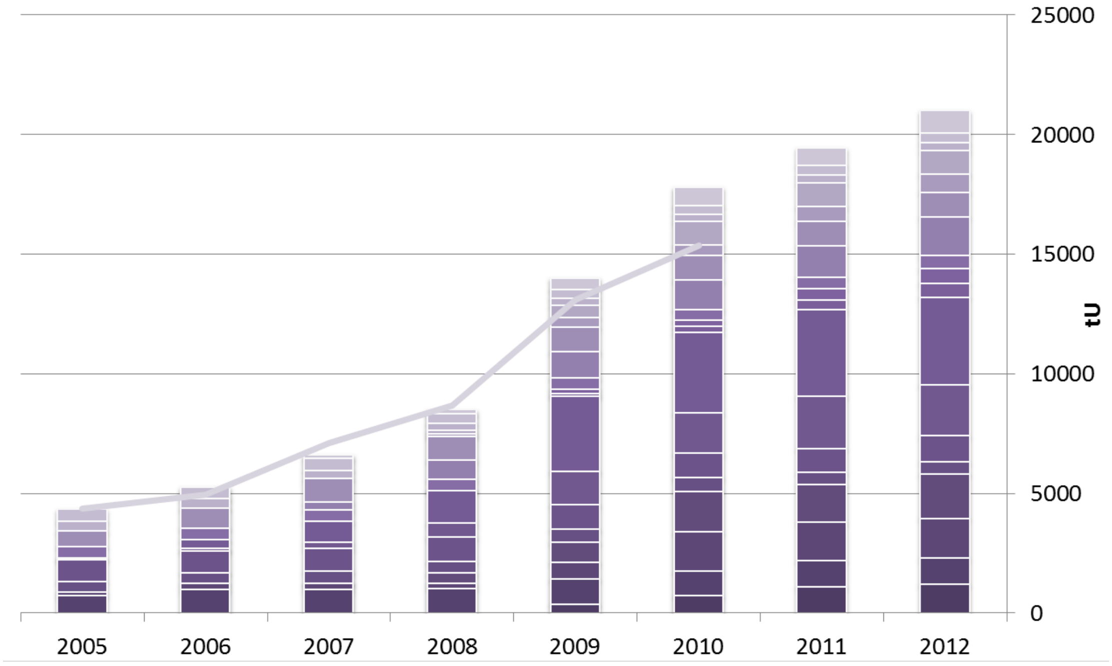

FIGURE A-18: HISTORIC KAZAKH PRODUCTION MINE BY MINE[35]. THE LINE SHOWS KAZATOMPROM'S PLANNED PRODUCTION IN FRAME OF THE PROGRAM "15000 TU BY 2010.

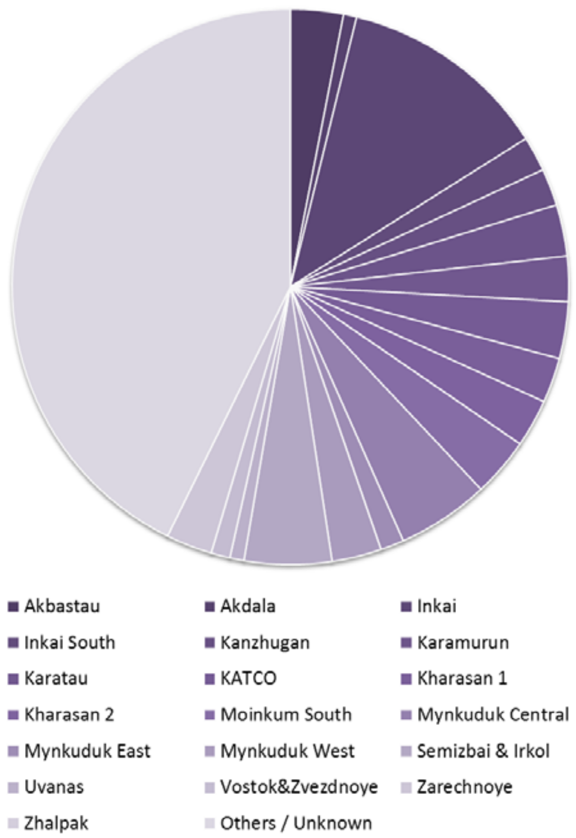

FIGURE A-19: DISTRIBUTION OF RAR - KAZAKHSTAN

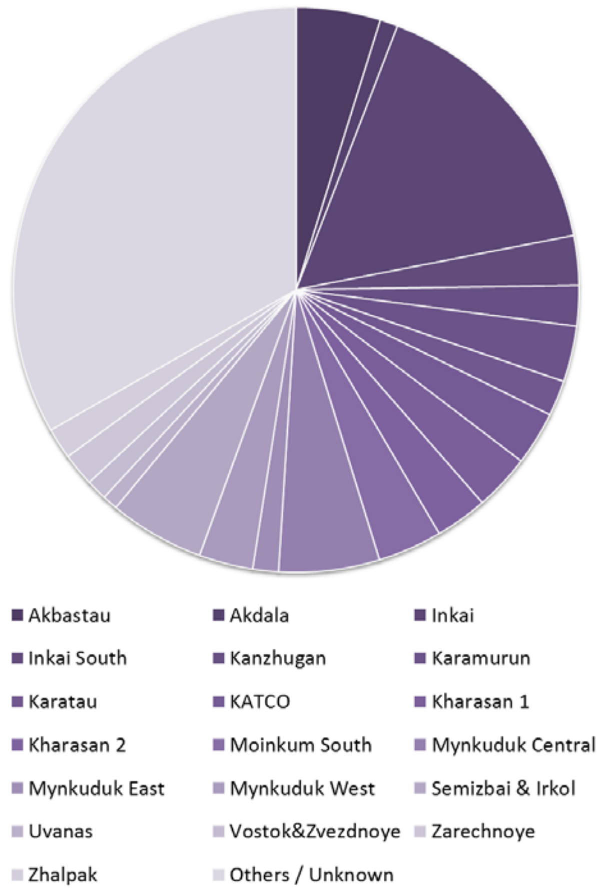

FIGURE A-20: DISTRIBUTION OF IR - KAZAKHSTAN

[35] Including estimates for some mines operated by Kazatomprom due to lack of data.

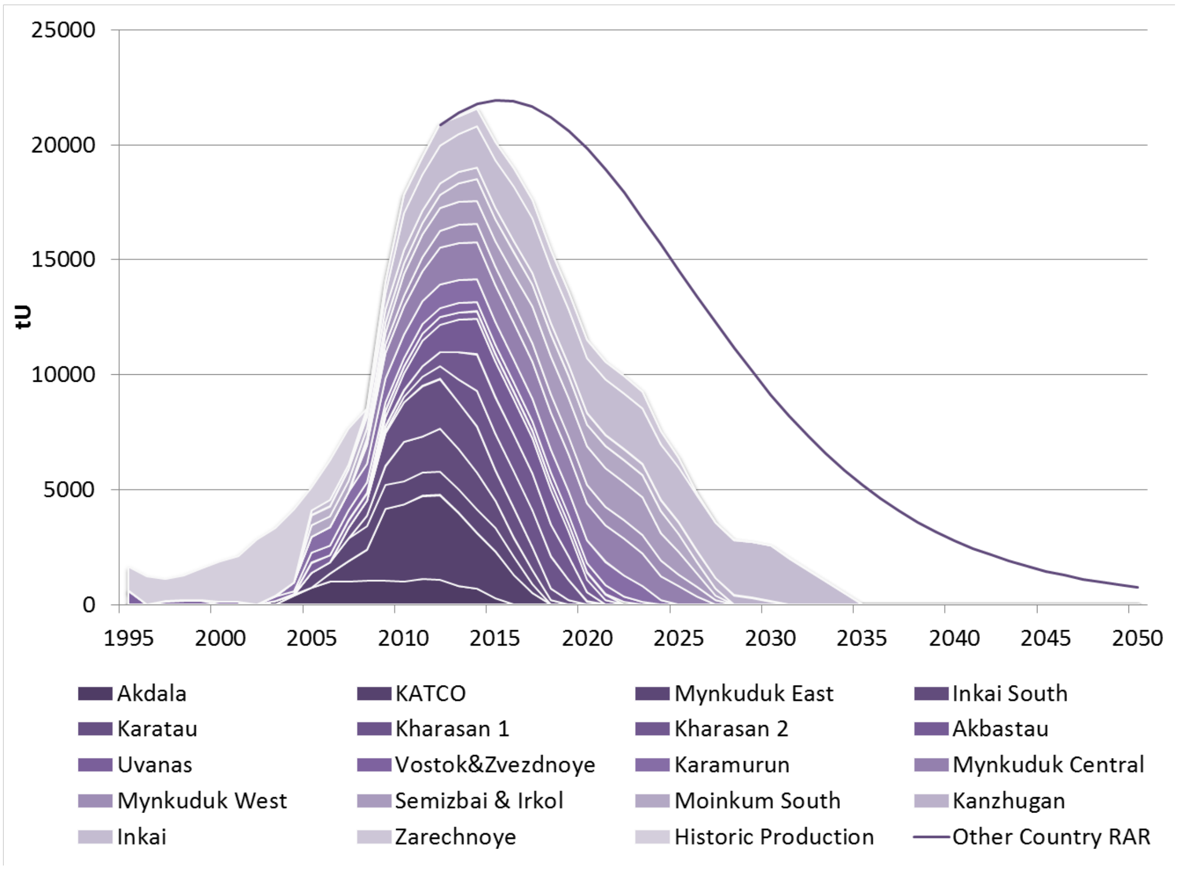

FIGURE A-21: KAZAKH PRODUCTION SCENARIO – RAR 1

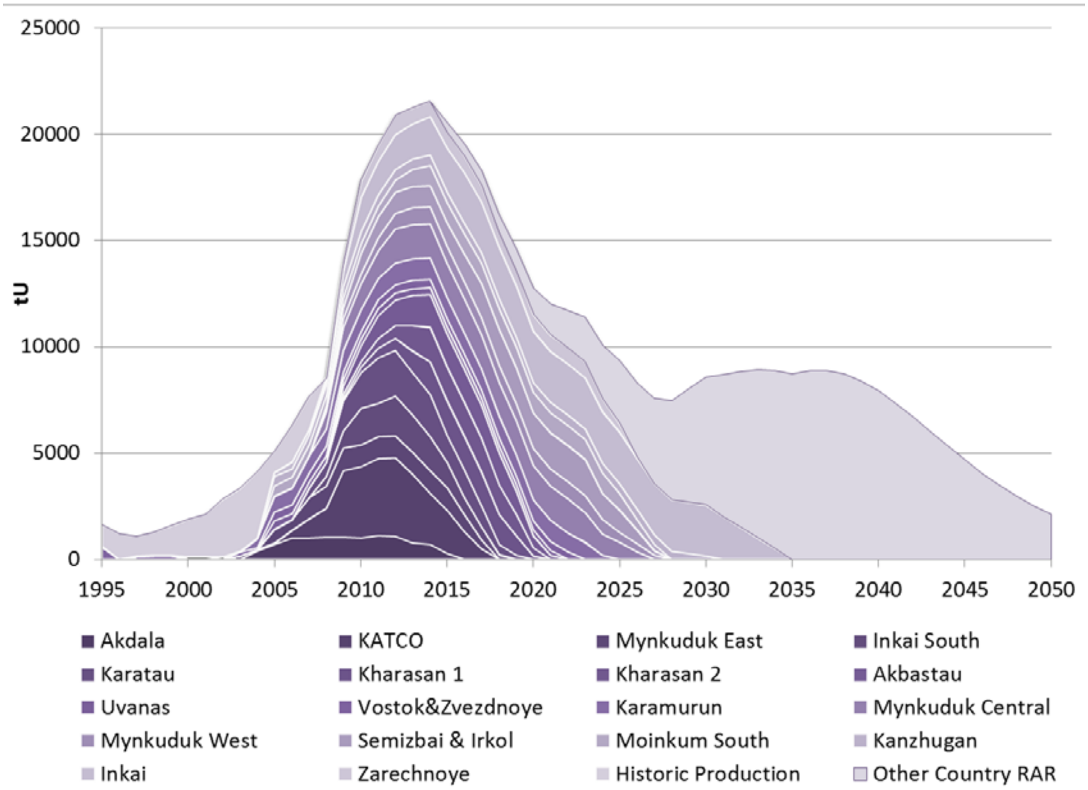

FIGURE A-22: KAZAKH PRODUCTION SCENARIO – RAR 2

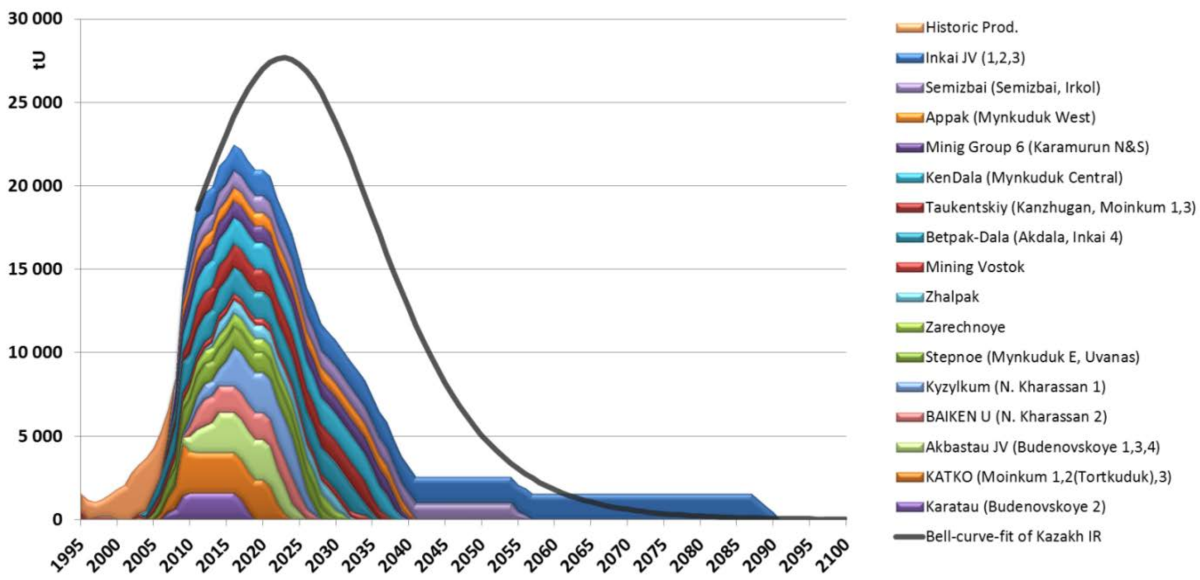

FIGURE A-23: PRODUCTION SCENARIO FOR KAZAKHSTAN BASED ON IDENTIFIED RESOURCES AT 80% LOAD FACTOR – IR 2009

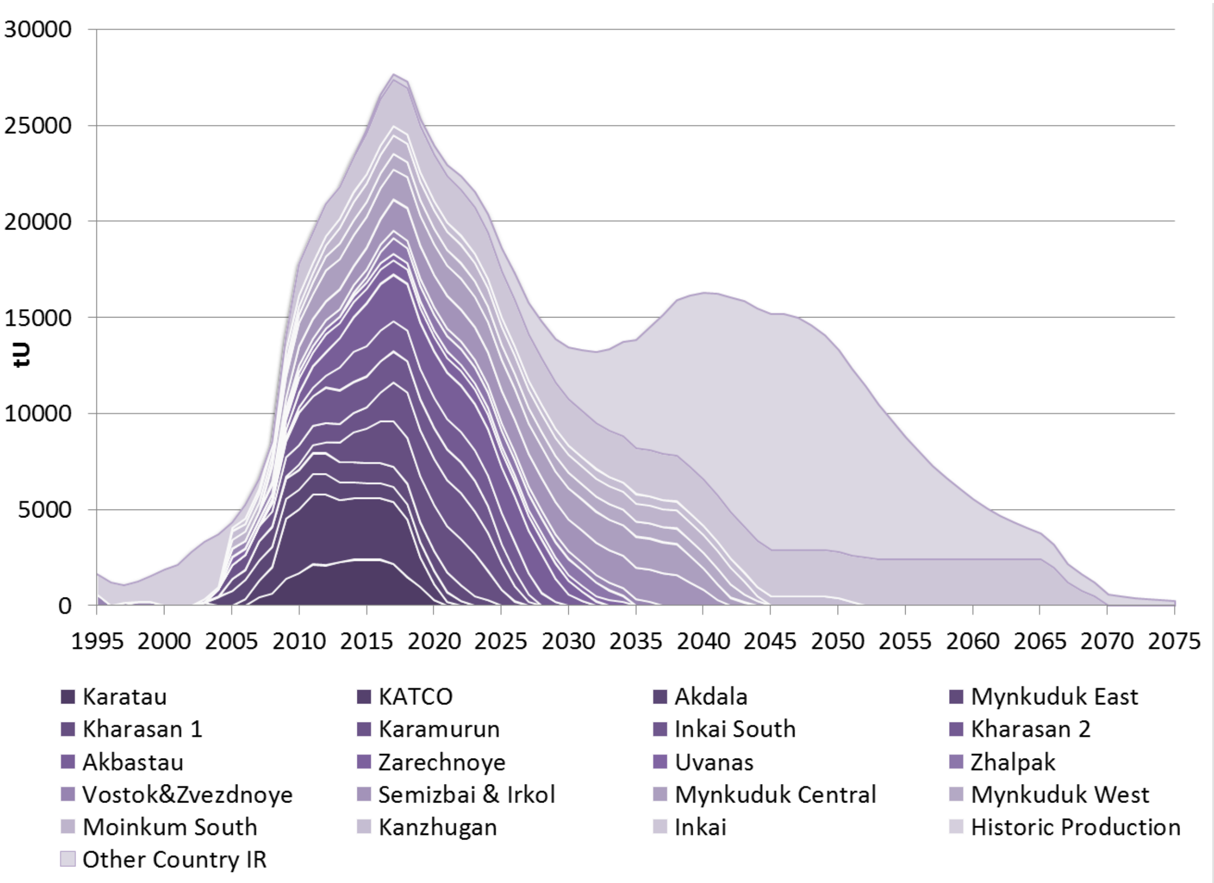

FIGURE A-24: KAZAKH PRODUCTION SCENARIO – IR 2012

NIGER

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity [tU]	Production 2012 [tU]
340 600	445 500	0.1	2	4 700	4 567

In Niger, the major uranium deposits are found in the center of the country. First discoveries have already been made in the late 50s, when Niger was still under French colonial rule. Today the majority owner of the two operating companies is the French company Areva.

A large share of the currently reported resources is related to the Imouraen deposit. It is thus not surprising that the production scenario is mainly dependent on the development of this deposit. A mining permit was issued in 2009; the start of operation is targeted for 2015.

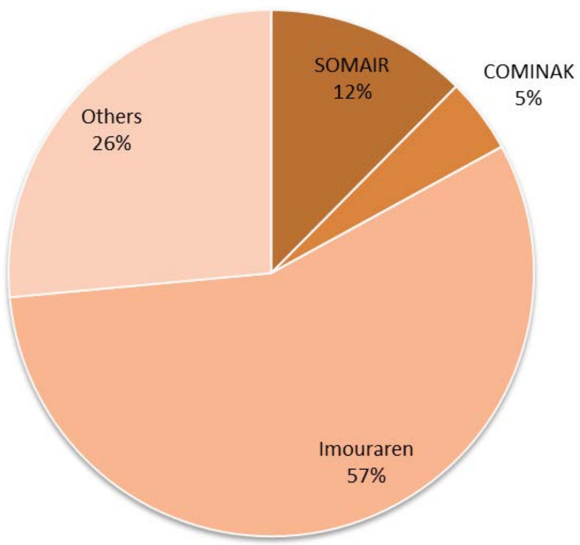

FIGURE A-25: DISTRIBUTION OF RAR - NIGER

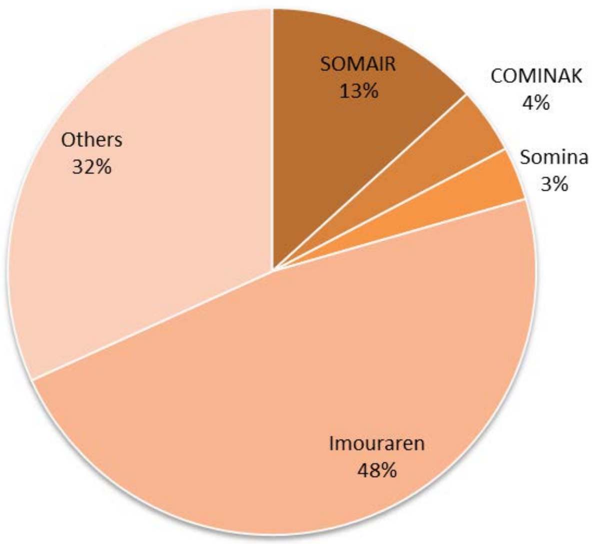

FIGURE A-26: DISTRIBUTION OF IR - NIGER

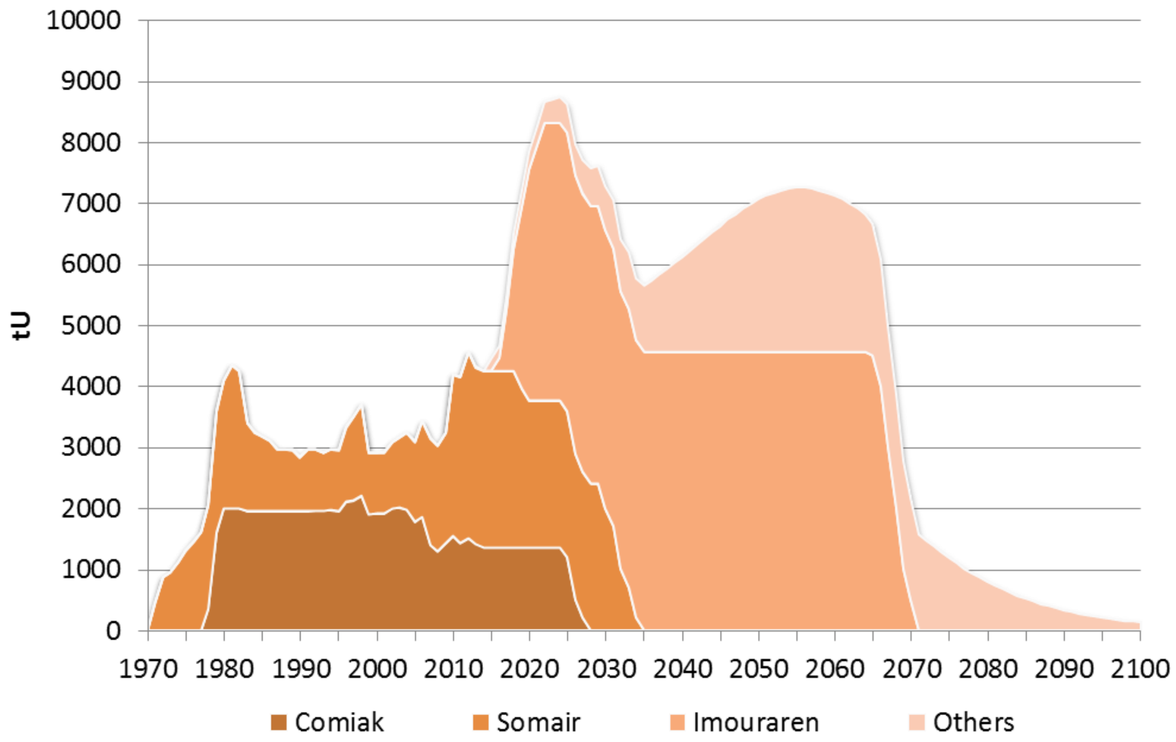

FIGURE A-27: NIGER PRODUCTION SCENARIO – RAR

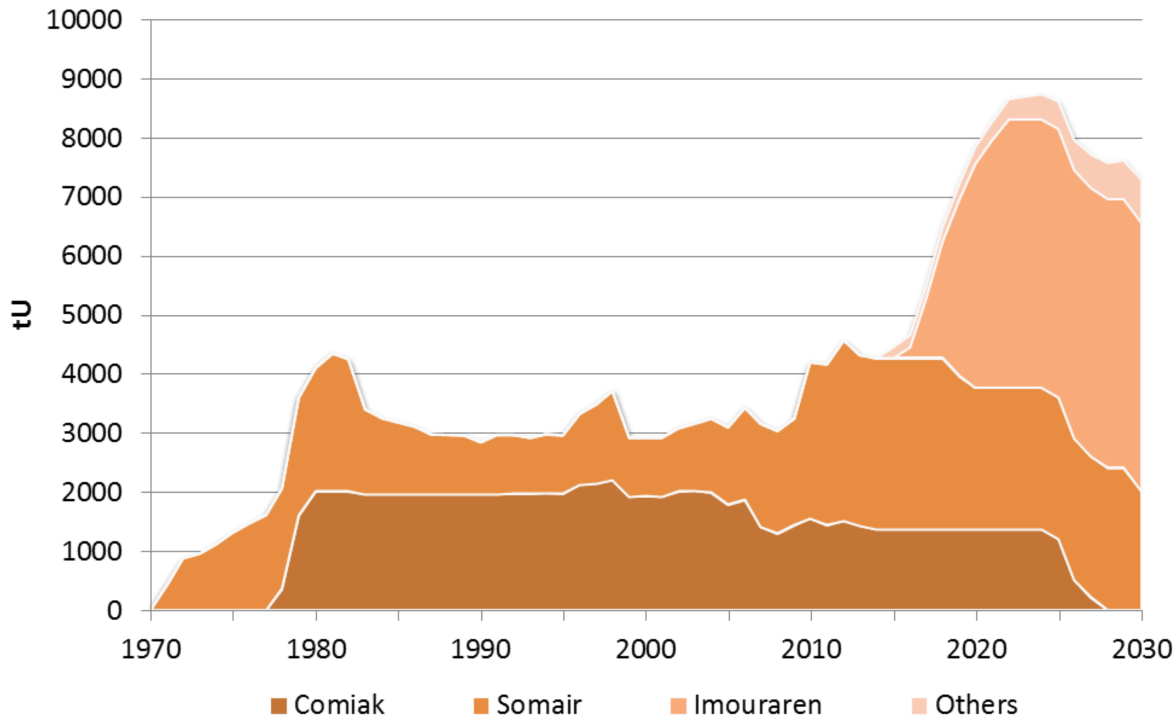

FIGURE A-28: NIGER PRODUCTION SCENARIO – RAR SHORT

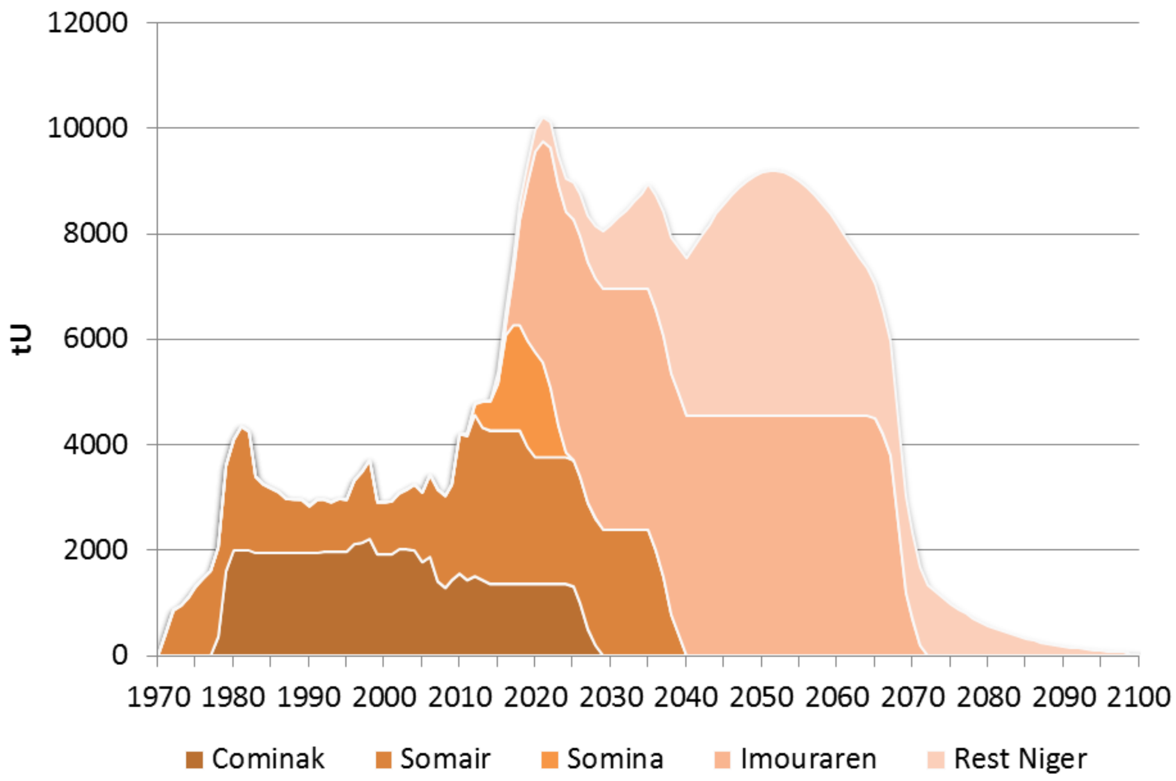

FIGURE A-29: NIGER PRODUCTION SCENARIO – IR

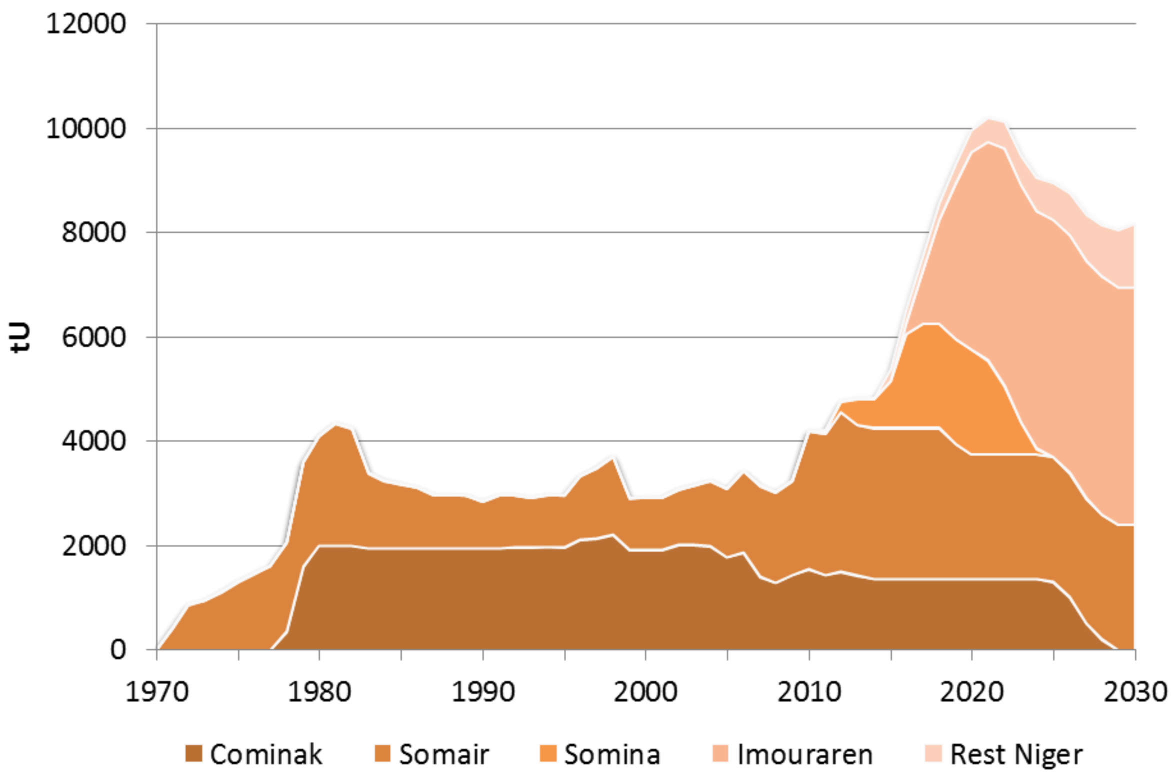

FIGURE A-30: NIGER PRODUCTION SCENARIO – IR SHORT

NAMIBIA

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity [tU]	Production 2012 [tU]
362 600	518 100	0.03	2	6 400	4 504

In Namibia the are currently two mines in operation, "Rossing" and "Langer Heinrich", which accounted for 7% of total world production in 2012 (4500 t U). A third mine called Trekkopje was put on maintenance recently due to unfavorable market conditions by its owner Areva, after producing some 400 tU in pilot production.

Compared to other countries the Namibian uranium resources have rather low grades, which is why development new projects proceeds rather slowly at the current market situation. Nonetheless there are some projects in development above all the Husab Mine, also known as Swakop, hosting about a third of the countries resources.

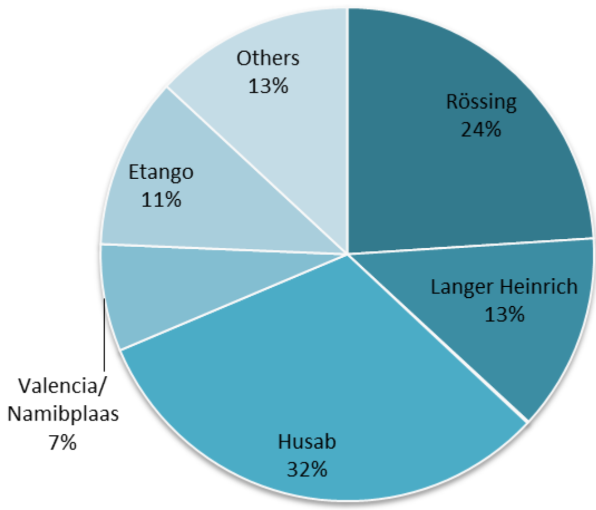

FIGURE A-31: DISTRIBUTION OF RAR - NAMIBIA

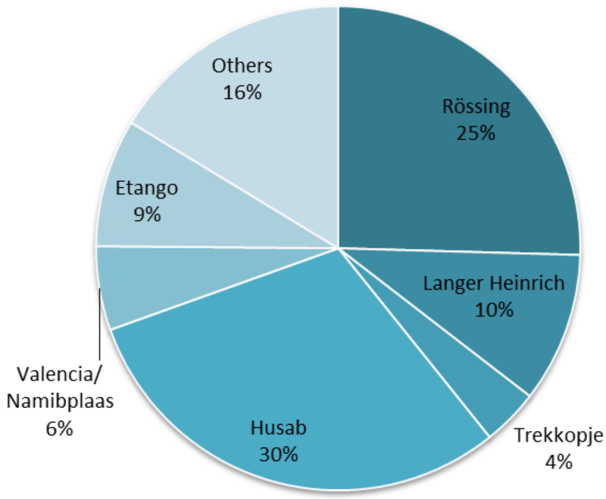

FIGURE A-32: DISTRIBUTION OF IR - NAMIBIA

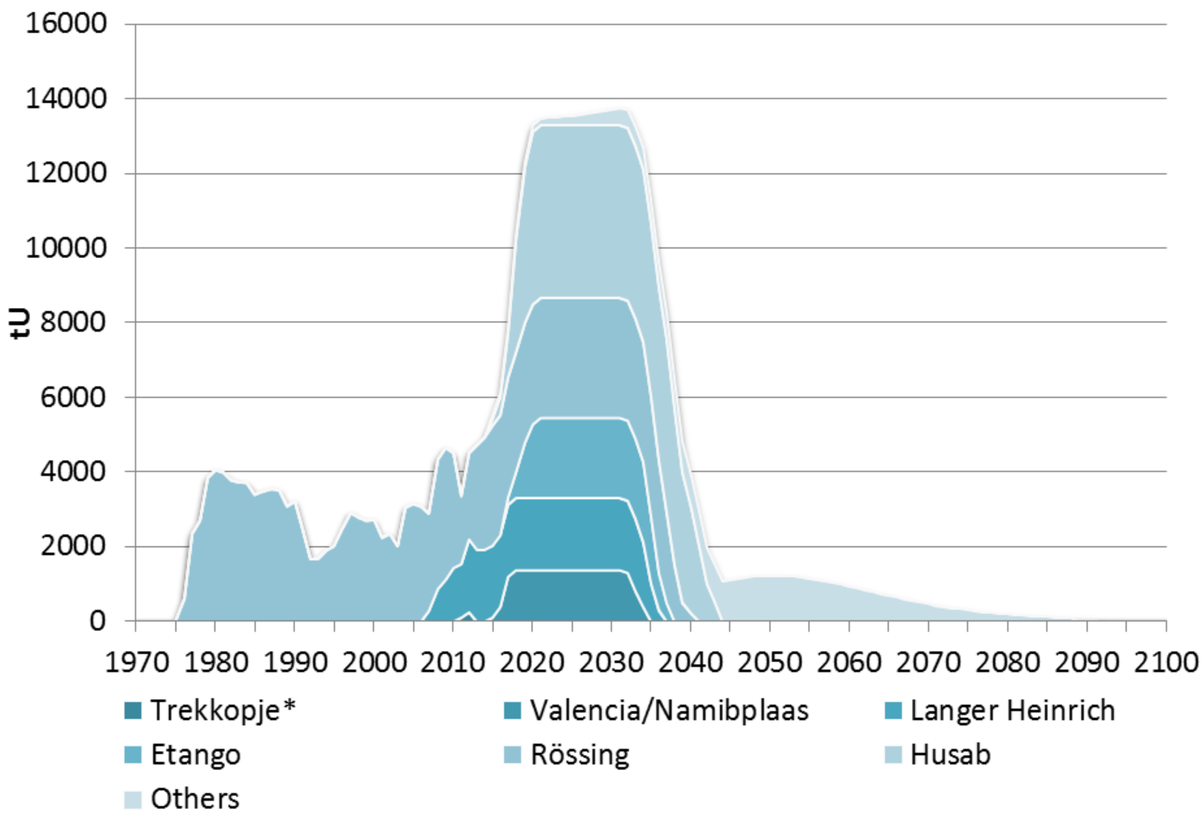

FIGURE A-33: NAMIBIA PRODUCTION SCENARIO – RAR

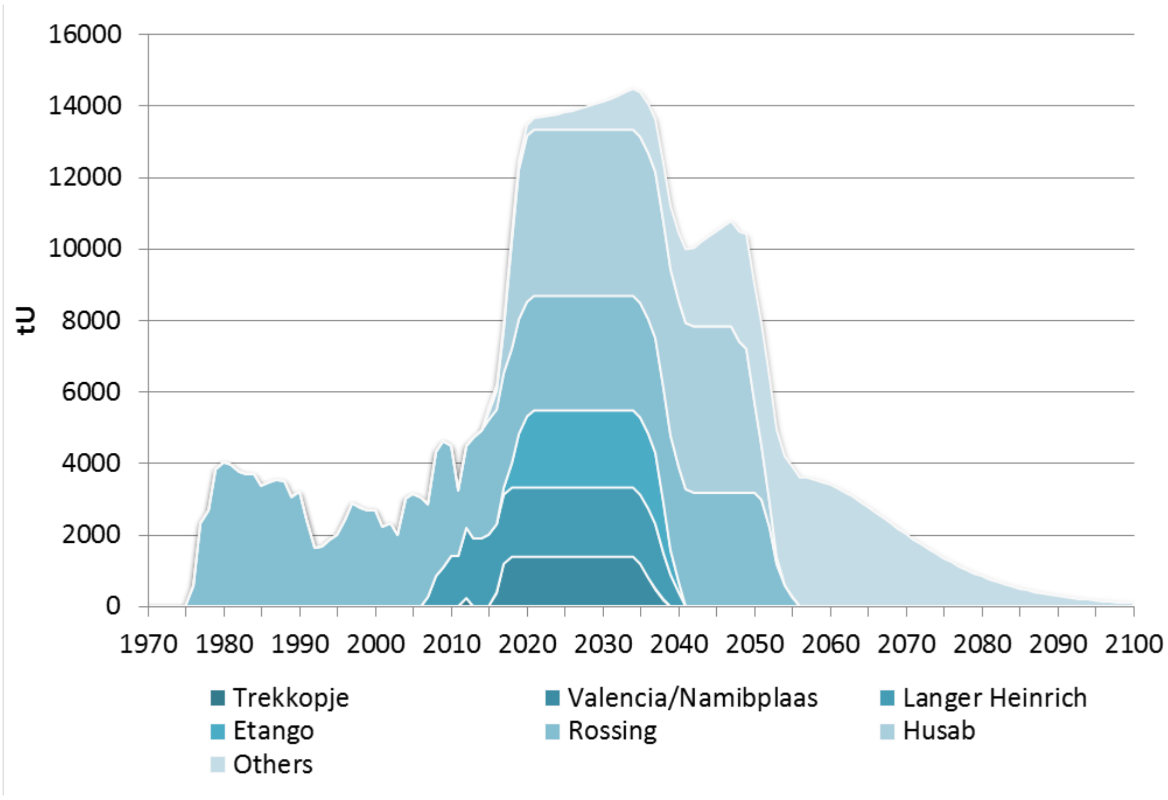

FIGURE A-34: NAMIBIA PRODUCTION SCENARIO – IR

RUSSIA

RAR [tU]	IR [tU]	Average Grade of IR [%]	Operating mines	Total capacity [tU]	Production 2012 [tU]
218 300	650 300	0.14	2	4 300	2 900

Uranium production in Russia has always been in the range of 3000 - 4000 t U in recent years, with production slightly decreasing in the last 2 years due to low ore grades at the Priargunsky mine. Two other mines (both ISL) are in operation in the country: Dalur is in commercial operation; Khiagda is still in a pilot phase. Exploration and mining operations are in the hands of state-owned company Atomredmetzoloto (ARMZ).

As for resources, Russia can be found on the 7th place for RAR and 3rd place for IR. 50% and 40% respectively can be found in the Elkon deposit, which is estimated to be the second largest uranium deposit in the world.

Plans announced in 2007 to achieve some 12000 tU output in 2020 (WNA, 2013g)seem out of question at the moment, especially due to delays in the startup of a mine at the Elkon deposit, which is now planned for 2020.

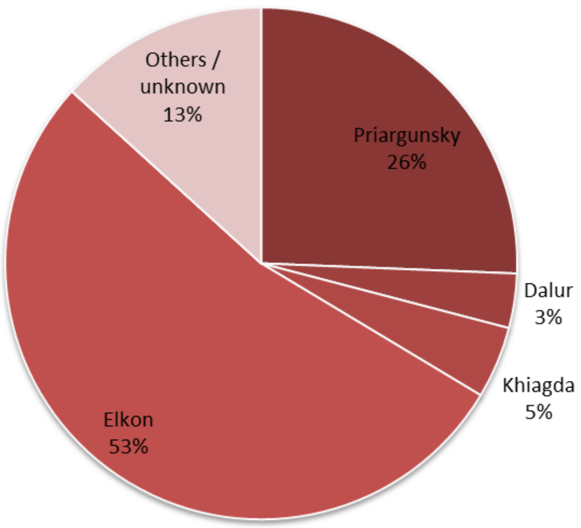

FIGURE A-35: DISTRIBUTION OF RAR – RUSSIA 2011

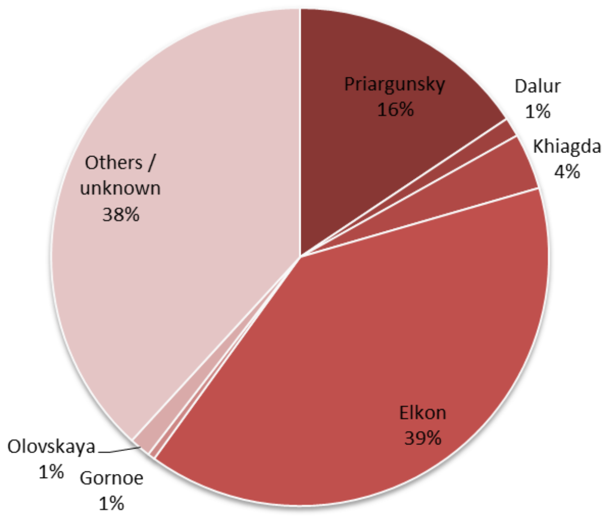

FIGURE A-36: DISTRIBUTION OF IR – RUSSIA 2011

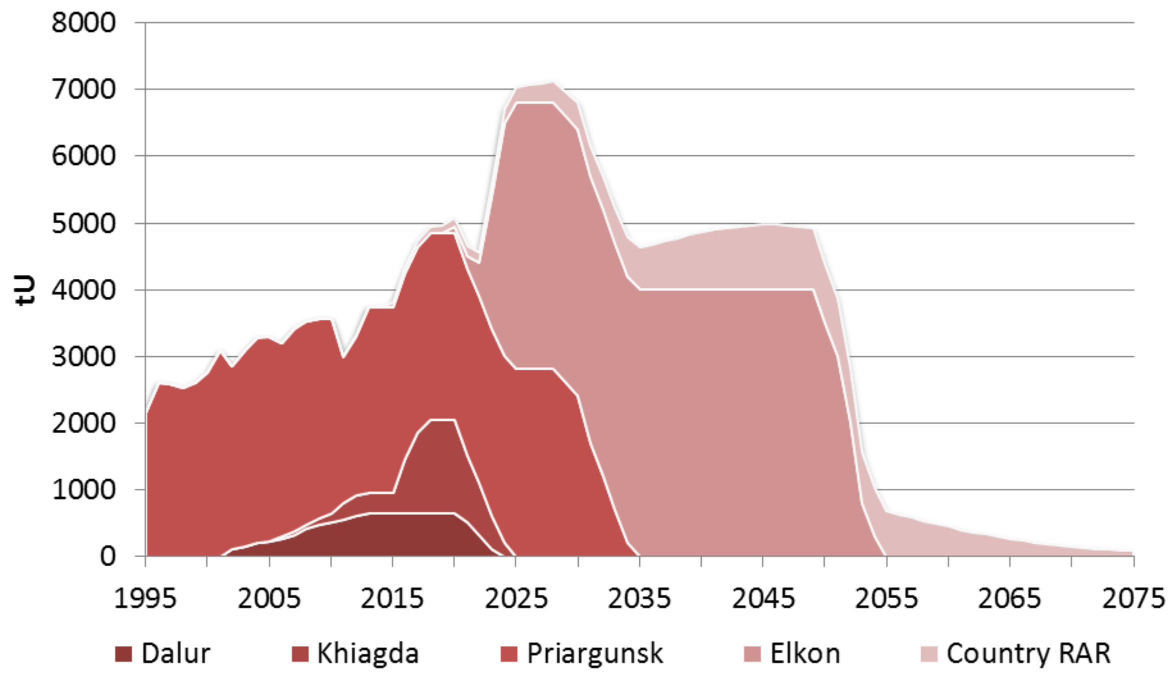

FIGURE A-37: RUSSIA PRODUCTION SCENARIO – RAR

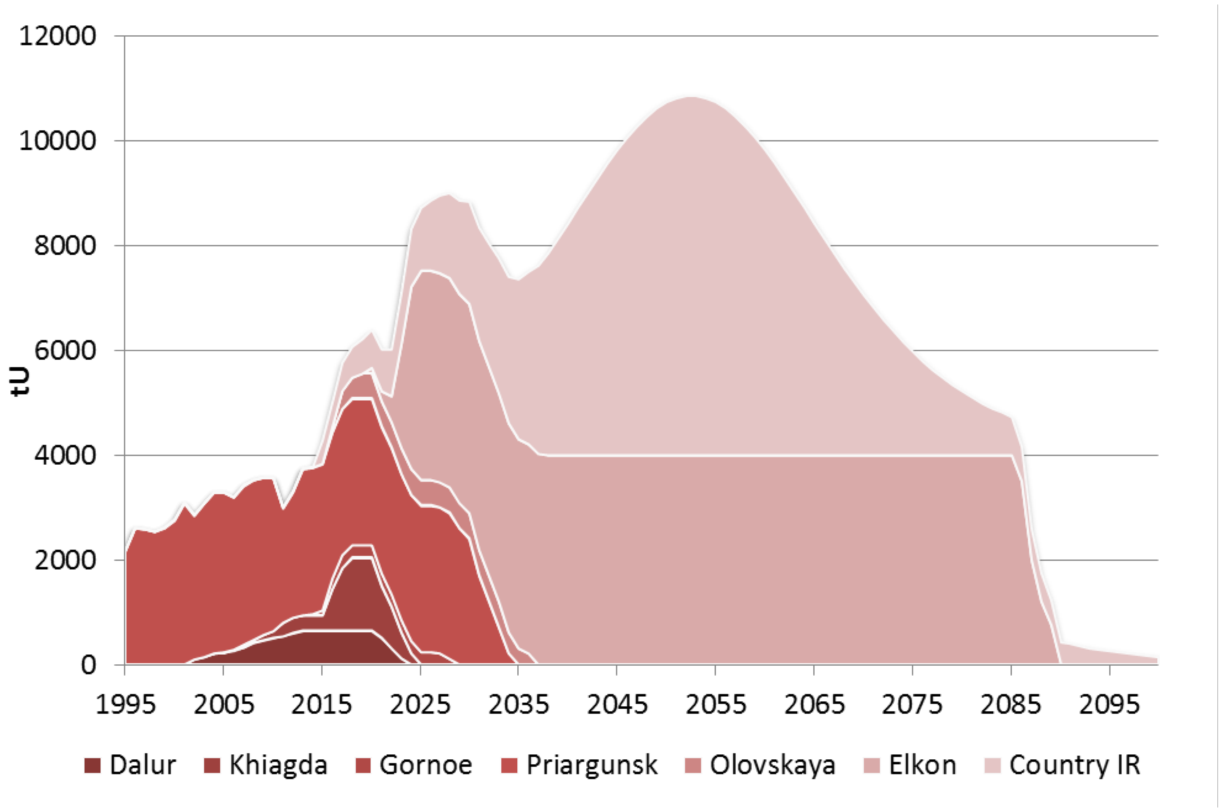

FIGURE A-38: RUSSIA PRODUCTION SCENARIO – IR