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Long Term Sustainability of Nuclear Fuel Resources

Dubravko Pevec, Vladimir Knapp and Krešimir Trontl
University of Zagreb, Faculty of Electrical Engineering and Computing
Croatia

1. Introduction

The basic issue in considering the contribution of nuclear power to solving the world's energy problem in the future is the availability of uranium resources and its adequacy in meeting the future needs of nuclear capacity. Increased interest in nuclear energy is evident, and a new look into nuclear fuel resources is relevant. Sufficiency of nuclear fuel for the long-term use and expansion of nuclear power has been discussed by individual analysts and by institutions, with wide spectrum of answers corresponding to variety of initial assumptions on uranium resources, reactor technologies and energy strategies (Fetter, 2009; Nifenecker, 2003; Pevec et al., 2008). With a suitable choice of assumptions arguments were occasionally constructed for the claim that nuclear power has no long-term future due to inadequate fuel resources. Oppositely, again with appropriate choice of assumptions, reassuringly long times of nuclear fuel availability were obtained, even with inefficient once-through open nuclear fuel cycle. Typical such scenarios assume extension of present slow growth of nuclear power or assume a constant share of nuclear power in the total world energy production, now slightly above 6%. With once-through fuel cycle resources then may last well over a hundred years, as will be shown below, and, argument goes on, by that time we will have nuclear fusion, so there is no reason for concern about nuclear fuel. At present state of world affairs we cannot afford the comfort of such reasoning as it neglects the outstanding potential of nuclear energy to contribute to the solution of the probably crucial problem facing humanity; how to stop climate changes threatening our civilisation, and how to do it urgently. Unlike various alternative CO_2 non-emitting energy sources, fission energy is technically developed and available now, as witnessed by close to 430 reactors in operation (Knapp et al., 2010).

The nuclear energy has some characteristics different from fossil fuel energy which are very important when considering the long term sustainability of nuclear fuel resources.

First, unlike in the case of fossil fuels, the amount of energy obtainable from the resources per unit mass of nuclear fuel is far from being a fixed figure. Energy content of a kg of the standard coal is 29. 3 MJ. It is usable with high percentage of this figure for heating and with 30-40% if converted to electricity. Energy that can be obtained from a kg of natural uranium is highly dependent on the reactor type and on the nuclear fuel cycle. Presently dominant are so called thermal reactors. Their physically most important feature is that they fission practically only uranium isotope U235 which is present in natural uranium in only 0.7%. By presence of moderator in the core of these reactors fission neutrons are thermalised and thereby fission probability of U235 is increased by a large factor. Due to their even-even proton-neutron structure U238 nuclei can be fissioned only by fast neutrons. However, they can absorb slow neutrons and through two decays then U239 transform into a fissionable isotope of plutonium, Pu239, with properties similar to those of U235. As U235, it is fissionable by thermal neutrons and energy release per fission only slightly higher, some 2%. Consequently, in thermal reactors by neutron absorption a small amount of U238 is converted in plutonium, mainly Pu239. Plutonium is partly burnt in parallel with U235 and partly remaining in spent fuel. The thermal energy obtained per unit mass of the fuel in present thermal reactors is given in Table 1. Much the largest part of dominant isotope U238 remains unused. If plutonium is extracted from the spent fuel it can be added to the fresh fuel thereby increasing the amount of energy obtained from the unit weight of natural uranium. As the content of U238 in uranium is 99.3%, clearly a dramatically larger quantity of energy would be obtained if the energy of this isotope could be released (Bodansky, 2004).

Fuel	Enrichment	Energy per Unit mass		
Nat. uranium	0.711%	584 GJ/kg	6.8 MWd/kg *	7.3 MWd/kg **
Enriched U	3.5%	2870 GJ/kg	33.3 MWd/kg *	36-40 MWd/kg **
Plutonium	100%	82100 GJ/kg	950 MWd/kg	

* from fission of U235 only ** in reactor, with contribution from plutonium

Table 1. The thermal energy obtained per unit mass in present thermal reactors

Second, contribution of uranium cost to the cost of nuclear-generated electricity is low (2-4%) compared to contribution of fossil fuel cost to the cost of electricity of fossil power plant (25% for coal and 65% for gas). It follows that, even for conservative approach of 4% uranium cost contribution to electricity cost, five-fold increase in uranium cost would increase the cost of electricity by 16%, and ten-fold increase in uranium cost would have modest effect on the cost of electricity by increase of 36%. It will be shown that these large increases in uranium price would produce much larger increases in available uranium resources. These uranium resources will be sufficient to support an inefficient once-through fuel cycle till the end of the century and beyond, even in the case of rapid nuclear capacity growth.

Third, the operational lifetime of nuclear power plants is considerably longer than fossil power plant operational lifetime. The operational lifetime of current nuclear power plants is 40-60 years, and for Generation III nuclear power plants it will be 60-80 years. Therefore, the changes in nuclear fuel utilization will slowly change for long time periods.

In this chapter we address the issue of nuclear fuel resources long term sustainability in relation to the expected and projected high limit of growth of the world nuclear power. Three main aspects have to be analyzed in order to estimate how long the world's nuclear fuel supplies will last: nuclear fuel resources (uranium and thorium), technologies for nuclear fuel utilization, and energy requirements growth scenarios including different scenarios for nuclear share growth.

In the second section of this chapter conventional and unconventional uranium and thorium resources were presented and discussed. Figures given are valid for particular moment of time, with the rate of change of estimates dependent on the intensity of research and exploration.

Detailed analysis of potential technologies for improved nuclear fuel utilization is required in order to assess long term sustainability of nuclear fuel resources. Nowadays, thermal converter reactor technology with once-through nuclear fuel cycle is dominant. The effectiveness of the technology can be improved in the area of enrichment process as well as by introducing reprocessing of the spent fuel on larger scale. Other technologies are also on the development stage that allows their implementation in short or medium period of time. These include: thermal and fast breeder reactors of different kind, thorium based fuel cycle, and conversion of uranium or thorium by particle accelerators or fusion devices. The potential technologies for improved nuclear fuel utilization are analyzed in the third section.

Very important aspect of long term sustainability of nuclear fuel resources are scenarios for energy requirements growth, and scenarios for growth of nuclear share in electricity production resulting in overall nuclear capacity growth. The low growth scenario, the high growth scenarios with exponential and linear increases, and the scenario based on a compromise between low and high growth assumptions are presented in the fourth section.

The long term sustainability of nuclear fuel resources is discussed in fifth section, and the conclusions are given in the sixth section.

2. Nuclear fuel resources

Uranium, as well as thorium, can be used as a nuclear fuel.

Uranium is relatively abundant element in the upper earth's crust with the average content of 3 ppm. Uranium is a significant constituent of about hundred different minerals, but most minable ores belong to a dozen minerals (e.g. uraninite, davidite, uranothorite, carnotite, torbernite, autunite, etc.). Usually, uranium deposits are classified into four types: vein-type deposits, uranium in sandstones, uranium in conglomerates, and other deposits (pegmatites, phosphates).

The existing nuclear power reactors use uranium as a fuel. Uranium is natural element composed mainly of two isotopes U238 (99.27%) and U235 (0.72%). As the existing nuclear power reactors are thermal reactors, the bulk of the produced energy is obtained by fission of U235 isotope.

Thorium is three times more abundant element than uranium in the upper earth's crust with the average content of 6 - 10 ppm. Thorium is widely distributed in rocks and minerals, usually associated with uranium, elements of the rare-earth group and niobium and tantalum in oxides, silicates and phosphates. Thorium is natural element composed of only one isotope Th232 (100%). Although the Th232 isotope is not fissile, it can be converted to fissile isotope U233 by slow neutron absorption.

2.1 Uranium resources

Uranium resources are broadly classified as either conventional or unconventional. Conventional resources are those that have an established history of production where uranium is a primary product, co-product or an important by-product. Very low grade resources or those from which uranium is only recoverable as a minor by-product are considered unconventional resources.

Resource estimates are divided into separate categories according to different confidence level of occurrence, as well as on the cost of production.

2.1.1 Conventional uranium resources

The Red Book published in 2010 (Organization for Economic Co-operation and Development Nuclear Energy Agency [OECD/NEA] & International Atomic Energy Agency [IAEA], 2010) categorizes conventional uranium resources into Identified resources (corresponding to previously "Known conventional resources") and Undiscovered resources. Identified resources consist of reasonably assured resources and inferred resources. 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. RAR have a high assurance of existence and they are expressed in terms of quantities of uranium recoverable from minable ore.

Inferred Resources (IR) refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence, in extension 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. The estimates in this category are less reliable than those in RAR. IR is corresponding to Estimated Additional Resources Category I (EAR-I) used up to the year 2003. IR is expressed in terms of quantities of uranium recoverable from minable ore.

Undiscovered resources include Prognosticated resources and Speculative resources.

Prognosticated Resources (PR) refers to uranium, in addition to Inferred Resources, that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on the knowledge of deposit characteristics in known deposits within the respective trends of areas and on such sampling, geological, geophysical or geochemical evidence as may be available. The estimates in this category are less reliable than those in IR. PR is corresponding to Estimated Additional Resources Category II (EAR-II) used up to the year 2003. PR is expressed in terms of uranium contained in minable ore, i.e., in situ quantities.

Speculative Resources (SR) refers to uranium, in addition to Prognosticated Resources, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. Existence and size of such resources are speculative. SR is expressed in terms of uranium contained in minable ore, i.e., in situ quantities.

The Identified resources amount to 6.306 million tonnes (4.004 million tonnes of RAR and 2.302 million tonnes of Inferred resources). The Undiscovered resources amount to 10.401

million tonnes (2.905 million tonnes of Prognosticated resources and 7.496 million tonnes of Speculative resources). These estimates refer to uranium recoverable at cost of less than 260 USD/kg. Total conventional resources amount to 16.707 million tonnes according to Red Book as of January 2009. The Identified conventional resources for different cost ranges are given in Table 2. The Undiscovered conventional resources for different cost ranges are given in Table 3.

Resource category	**Cost ranges**			
	< 40 USD/kgU	**< 80 USD/kgU**	**< 130 USD/kgU**	**< 260 USD/kgU**
Identified Resources (Total)	796	3742	5404	6306
Reasonably Assured Resources (RAR)	570	2516	3525	4004
Inferred Resources (IR)	226	1226	1873	2302

Table 2. Identified conventional resources for different cost ranges in the year 2009 (1000 tU)

Resource category	**Cost ranges**	
	< 130 USD/kgU	**< 260USD/kgU**
Undiscovered Resources (Total)	6553	10401
Prognosticated Resources (PR)	2815	2905
Speculative Resources (SR)	3738	7496

Table 3. Undiscovered conventional resources for different cost ranges in year 2009 (1000 tU)

Countries with major uranium resources are Australia, Kazakhstan, Russian Federation, Canada, Niger, South Africa, USA, Namibia, and Brazil.

2.1.2 Unconventional uranium resources

Unconventional uranium resources (Barthel, 2007) are found in low grade deposits, or are recoverable as a by-product. Low grade uranium deposits in black shales, lignites, carbonatites and granites were expected to be potential sources in the past. However, developing a cost effective, environmentally acceptable means of uranium extraction from this potential source remains a challenge. By-product resources are of interest in the case that conventional resources are insufficient. In by-product recovery, the greatest portion of the costs is borne by the main products.

The most important unconventional uranium resources reported in Red Book 2010 (OECD/NEA & IAEA, 2010) are phosphate deposits and seawater.

2.1.2.1 Phosphate deposits

At higher cost, uranium can be extracted from phosphate deposits. Uranium contained in phosphate deposits is estimated at 22 million tonnes, although annual production is limited by annual phosphoric acid production. The upper limit is below 10 000 t/year, so even if all the phosphoric acid production over time were considered, the total addition would not exceed one million tonnes. The historical operating costs for uranium recovery from phosphoric acid range from 60 to 140 USD/kgU (World Information Service of Energy [WISE], 2010). Recently, a new process (PhosEnergy) is being developed by Uranium Equities Limited, offering uranium recovery costs in the range from 65 to 80 USD/kgU. Design and construction of the demonstration plant is complete. It is expected to be in operation from late 2011 (World Nuclear Association [WNA], June 2011b). However, should uranium extraction, decoupled from phosphoric acid production, cost less than 200 USD/kgU an abundant addition to conventional resources would become available.

We do not assume that this will happen much sooner than 2060 and, thus, base our consideration on estimated conventional resources.

2.1.2.2 Uranium from the seawater

The uranium concentration in seawater is only 0.003 ppm, yet it can be extracted. It would require the processing of huge volumes of seawater (about 350 000 t water for 1 kg U) and use large amounts of absorber. The cost of extraction from seawater can be regarded as the upper limit of the cost of uranium. The quantity of uranium in the sea is about 4 billion tonnes, exceeding any possible needs for thousands of years.

Research on uranium recovery from seawater has been going in Germany, Italy, Japan, the United Kingdom and the United States of America in 1970s and 1980s, but is now only known to be continuing in Japan. Recent Japanese research showed that uranium extraction from the seawater is technically possible. It has been developed on a laboratory scale by using either resins or other specific adsorbent. An extraction cost as low as 250 USD/kg U has been estimated, which is more than twice as high as the present spot market price (Tamada et al., 2006). Although this price appears high, and certainly is, it could be acceptable for fast breeders with a closed fuel cycle.

2.2 Thorium resources

The principal sources of thorium are deposits of the placer type (concentrations of heavy minerals in coastal sands), from which monazite and other thorium bearing minerals are recovered. Thorium often occurs in minerals that are mined for another commodity and thorium being recovered as a by-product. Thorium is present in seawater with a concentration of only about 0.00005 ppm, due primarily to the insoluble nature of its only oxide, ThO_2. Thus the recovery of thorium from seawater is not a realistic option.

Estimates of thorium resources have been given in Red Books since 1965. Classification of thorium resources is similar to uranium, e.g. Reasonably Assured Resources (RAR) and Estimated Additional Resources (EAR). The EAR is separated into EAR-Category I and EAR-Category II according to different confidence level of occurrence. Identified resources consist of RAR and EAR-I. Prognosticated thorium resources are EAR-II. Thorium resources were also classified according to cost of recovery (OECD/NEA & IAEA, 2010).

The total world thorium resources, irrespective of economic availability, are at present estimated at about 6 million tonnes. The thorium resources recoverable at a cost lower than

80 USD/kg are estimated at 4.5 million tonnes. The identified thorium resources amount to 2 million tonnes and the prognosticated thorium resources amount to 2.5 million tonnes.

Countries with major thorium resources are Commonwealth of Independent States (former Soviet Union countries), Brazil, Turkey, USA, Australia, and India.

Due to the fact that thorium is roughly three times more abundant than uranium in the earth's crust and that exploration of thorium resources is poor, it is to be expected that ultimately recoverable thorium resources will be much higher than uranium resources.

2.3 Long term perspectives of nuclear fuel resources

The nuclear fuel resources given in preceding sections are the today's resource estimates published in the Red Book, compendium of data on uranium and thorium resources from around the world (OECD/NEA & IAEA, 2010). It is interesting to compare resource estimates over time (OECD/NEA, 2006). The evolution of Identified Resources, RAR, and EAR-I/IR over time (1973 – 2009) recoverable at cost of less than 130 USD/kg is shown in Fig. 1.

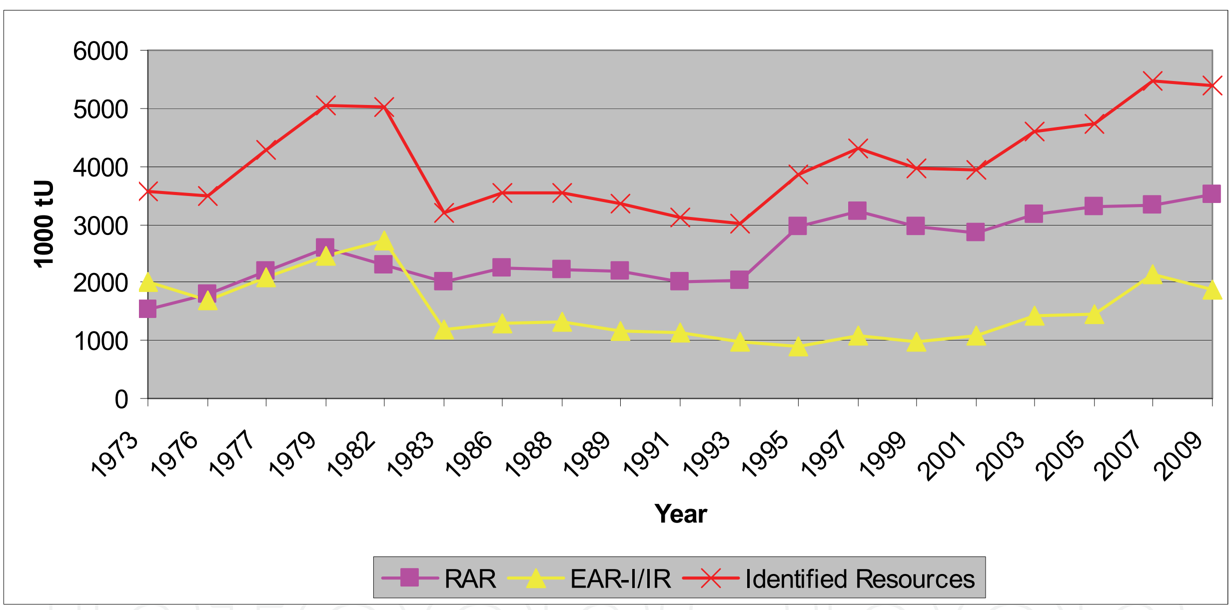

Fig. 1. Changes in Identified Resources, RAR, and EAR-I/IR over time (1973 – 2009)

The Identified Resources (including its components RAR and EAR-I/IR) mainly increased during a given time period except for a drop in year 1983. This drop could be explained by the facts that in year 1983 EAR have been subdivided into Category I and Category II and since 1983 RAR and EAR-I are given as recoverable resources(mining and milling losses deducted). The Identified Resources increased by around 60% in a time period of almost 40 years although for many years investment in exploration for uranium resources has been low.

The evolution of Undiscovered Resources, EAR-II/PR, Speculative Resources (< 130 USD/kgU), and Speculative Resources (regardless of the price) over time (1985 – 2009) is shown in Fig. 2.

The EAR-II/PR curve shows very gradual increase for the initial and final part of the given time period and for the rest of time period it remains nearly unchanged. That nearly unchanged part of the curve could be explained at least in part by the fact that countries tend to not re-evaluate their EAR-II/PR estimates on a regular bases. In contrast with the EAR-II/PR trends, both categories of Speculative Resources show considerably more volatility.

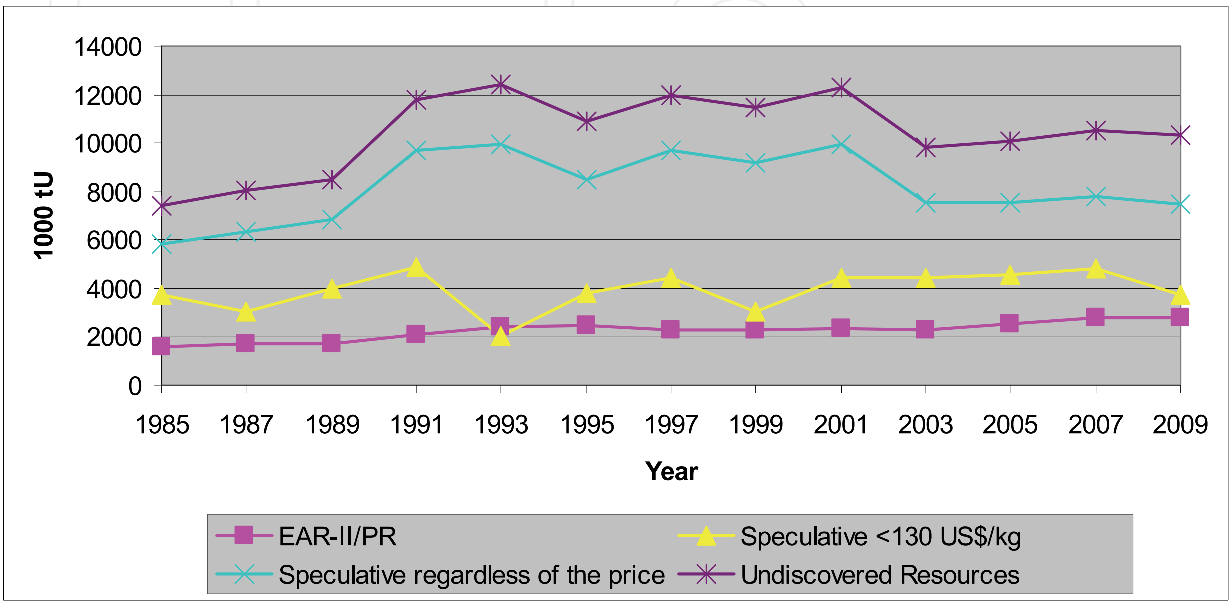

Fig. 2. Changes in Undiscovered Resources, EAR-II/PR, Speculative Resources (< 130 USD/kgU), and Speculative Resources (regardless of the price) over time (1985 – 2009)

The Red Book nuclear fuel resources estimates are obtained simply by collecting data on conventional resources from IAEA countries. Many countries are lightly explored in uranium and many countries do not report resources in all categories so there are almost certainly large quantities of uranium that are not yet included in Red Book. Therefore, the Red Book estimates of uranium resources should be considered a today's lower bound on the amount of uranium likely to be recoverable.

For analysis of uranium resources long term sustainability it is necessary to estimate the amount of uranium that will ultimately prove to be economically recoverable. This amount is defined as "total recoverable uranium resources". It depends on geologic parameters, as well as on development in technologies of exploration, extraction, and use. The total recoverable uranium resources could be determined from first principles by summarizing estimates of the abundance of uranium in the crust of the earth as a function of concentration and accessibility. Geologic data indicate that the total amount of uranium increases exponentially with decreasing ore grade. Synthesizing the power law for total amount of uranium and assumption that the cost of extracting a unit mass of uranium varies linearly with the inverse of the ore grade, one obtains a simple crustal model (Schneider & Sailor, 2008),

$$\frac{Q}{Q_0} = \left(\frac{P}{P_0}\right)^{\varepsilon}$$

where

Q = quantity (MtU) of uranium available at the price level P (USD/kg U)
Q_0 = quantity of uranium available at some reference price P_0
ε = long term elasticity of uranium supply.

This model must be calibrated through the selection of a reference point (P_0, Q_0) and the estimation of ε.

The Red Book data (OECD/NEA & IAEA, 2010) could be used as a reasonable point of departure for extrapolation of total recoverable uranium resources estimates. Therefore, the uranium resources quantity of 0,796 MtU available at price 40 USD/kgU (Table 2) has been selected as the reference point. The long term elasticity of uranium supply, ε, is estimated by different groups and its values range from 2.35 to 3.5. The World Nuclear Association (WNA, September 2011) concludes that a doubling in price from present levels could be expected to create about a tenfold increase in measured resources over time. It implies the long term elasticity of uranium supply, ε, to be equal 3.32. Another serious attempt to estimate how much uranium is likely to be available worldwide, based on Deffeyes and MacGregor (Deffeyes & MacGregor, 1980) distribution of uranium in the earth's crust, concluded that a ten-fold reduction in ore concentration is associated with a 300-fold increase in available resources. Using the assumption that costs are inversely proportional to ore grade the ε value of 2.48 is obtained. The U.S. Department of Energy Generation IV Fuel Cycle Crosscut Group (FCCG) study (United States Department of Energy [USDOE], 2002), basing itself on the amounts of uranium recently estimated to be available in the United States at 30 USD/kgU and 50 USD/kgU, predicted that that the ε might be as low as 2.35. Using the selected reference point and the obtained ε values, total recoverable uranium resources are calculated by simple crustal model for different cost ranges. The calculated values and the Red Book values given in MtU are shown in Table 4. These values range from 4 MtU for cost category of 80 USD/kgU to almost 400 MtU for cost category of 260 USD/kgU. All of these estimates suggest that the total amount of uranium recoverable at prices 130 USD/kgU and 260 USD/kgU is likely to be substantially larger than the amount reported in the Red Book.

Source of estimate	**ε**	**Cost ranges**			
		< 40 USD/kgU	**< 80 USD/kgU**	**< 130 USD/kgU**	**< 260 USD/kgU**
WNA	3.32	0.796	7.96	39.84	397.91
Deffeyes and MacGregor	2.48	0.796	4.44	14.8	82.59
Generation IV-FCCG	2.35	0.796	4.06	12.70	64.75
Red Book		0.796	3.742	5.402	6.306

Table 4. Total recoverable uranium resources estimated by simple crustal model for different cost ranges (MtU)

In our further analysis it was assumed that conventional uranium resources according to Red Book as of January 2009 in amount of 16.7 million tonnes will be recovered until year 2065.

Based on estimates obtained by simple crustal model we assumed that the total amount of uranium recoverable until the end of this century at still tolerable price of 180 USD/kgU is

50 Mt. This figure is supported by Update of the MIT 2003 Future of Nuclear Power study (Massachusetts Institute of Technology [MIT], 2009) in which "an order of magnitude larger resources are estimated at a tolerable doubling of prices".

3. Technologies for improvement of nuclear fuel utilization

A fuel utilization of present power reactors is low because they mainly utilize energy of U235 nuclide. Therefore, technologies and methods have been considered, that make possible to utilize enormous energy of U238 and of Th232 as well. Some of these technologies and methods are developed and proven technically viable, while some others are well researched with developmental problems identified. In the past, characterized by relatively slow nuclear energy expansion, with low cost of uranium and high cost of reprocessing of spent fuel, the simplest once-through fuel cycle has been generally accepted. Consequently, better utilization of nuclear fuel was not interesting to a private nuclear industry. Situation is different in the countries where governmental support made long term planning possible. For our purpose two aspects have to be understood. First, from the technical point of view, what these new technologies can achieve regarding uranium resources extension. Second important technical consideration is the time for their commercial development. It also has to be evaluated whether they could be introduced by the time of exhaustion of uranium resources used by present thermal reactors operating in the open cycle regime as is practice today. The following technologies and methods for improvement of nuclear fuel utilization have been considered:

a. Plutonium and uranium recycle with thermal reactor technology
b. Thermal breeder reactors
c. Fast breeder reactors
d. Zonal fuel burning in the so called „candle reactor"
e. Accelerator conversion of U238 into plutonium and of Th232 into U233
f. Conversion of U238 and Th232 by fusion neutrons

The short survey of each of the considered technologies and methods is given below.

3.1 Plutonium and uranium recycle with thermal reactor technology

Technology of plutonium recycle has been developing for many years. The PUREX process for recycling uranium and plutonium from spent nuclear fuel is implemented in several countries. Plutonium is mixed with enriched uranium for fabrication of the so called MOX fuel as both components are in the chemical form of oxides. There are many years of experience with the use of MOX fuel. Plutonium recycle is also a way to use surplus military plutonium. Except for such special situation, in the past there was little general interest in recycling at current high reprocessing and low uranium prices. Recent quantitative cost assessment of plutonium recycle has been given in EPRI Report 1018575 in 2009 (Electric Power Research Institute [EPRI], 2009). According to EPRI analysis fuel costs for once-through fuel cycle would be lower than for plutonium recycle for uranium cost below USD 312/kg and PUREX reprocessing cost above USD 750/kgHM. The same holds for uranium recycle except for some special concepts of reactors operating in tandem. The effect of plutonium and uranium recycle in present light water reactors on resources extension would not be very high; typically 5 kg of spent fuel contains enough plutonium for one kg of fresh fuel with plutonium replacing U235. Natural uranium resources extension is of the order of around 30%, as can be seen in a number of publications and reports (Garwin, 1998).

3.2 Thermal breeder reactors

Thermal breeder reactors were investigated in the early days of nuclear technology development before selection of light or heavy water cooled thermal reactors for commercial energy production. Thermal breeding is achieved either by benefiting from larger neutron yield of U233 in thermal fission, or by better neutron economy achieved by extracting neutrons absorbing fission products from the liquid fuel. First approach was investigated in the experimental Shippingport reactor. This light water solid fuel thermal breeder prototype reactor was in operation in US from 1957-1982 using uranium and thorium fuel, but the same concept could run on thorium fuel and U233 as fissile material produced by conversion of thorium. (United States Nuclear Regulatory Commission [USNRC], 2011). Other approach was also investigated in the early years of nuclear development. Small experimental molten uranium fluoride fuelled reactor (8 MW thermal power) was operated in the years 1965-69 at Oak Ridge National Laboratory in the US (Briggs, 1967; Rosenthal et.al., 1970). Using on-line extraction of fission products from circulating molten fuel, neutron losses by absorption in fuel were reduced with the effect of increasing conversion ratio above 1. Development did not proceed at the time due to corrosion problems. Latest development of this reactor type was Japanese FUJI MSR 100-200 MWe reactor. With several attractive features, such as reduced radioactivity inventory, low pressure of primary circuit, high thermal efficiency, possibility to run on thorium fuel, this concept is again taken up in a selection for Generation IV reactors. Corrosion problems were largely resolved in the meantime. Work on the molten salts technology is in progress in EU, China, India, with long interest in thorium, and other countries (Forsberg et.al., 2007; Gen. IV International Forum, 2011b).

Another concept of thermal breeder is a version of Canadian heavy water reactor CANDU using U233 as fissile material and thorium as fertile material. Commercial use of this fuel cycle, usable with little additional technical development required, depends on the costs of uranium and reprocessing of thorium for extraction of U233, and is ruled out at present uranium and reprocessing costs.

3.3 Fast breeder reactors

Concept of fast breeder reactor developed in early days of nuclear energy uses the physical property of Pu239 which when fissioned by fast neutrons releases considerably more fission neutrons than U235 or U233 fissioned at low or high neutron energy. Thus in reactor with Pu239 as fissile material and U238 as fertile, and with little or no moderation to avoid degradation of high neutron energy, conversion coefficient will be increased. With additional plutonium production by neutrons escaping from the reactor core into the uranium blanket surrounding the core, conversion ratio can reach values well above 1. Since these early days several concepts of fast reactors were developed to utilize energy of U238. One concept, sodium cooled fast reactors has been developed from the first small experimental reactor EBR 1 in USA, in operation 1951, to large reactors close to commercial stage, such as Superfenix of 1200 MW in France operating from 1984 to 1998, with a number of working prototypes in between in several countries. Last construction was reactor Monju of 300 MW in Japan, in operation from 1993. List of major experimental, pilot and demonstration fast breeder reactors is given in Table 5 (Cochran et.al., 2010; WNA, August 2011).

Country	Name	MWe	MWth	Operation
China	CEFR	20		2010-
France	Rapsodie		40	1967-1983
	Phenix	250		1973-2009
	Superphenix	1240		1985-1998
Germany	KNK 2	21		1977-1991
India	FBTR		40	1985-
	PFBR	500		2010?
Japan	Joyo		140	1977-
	Monju	280		1994-1995, 2010?
USSR/Russia	BR-5		5	1959-2004
	BOR-60	12		1969-
	BN-350 (Kazakhstan)	350		1972-1999
	BN-600	600		1980-
	BN-800	800		2014?
United Kingdom	Dounreay FR	15		1959-1977
	Protoype FR	250		1974-1994
United States	EBR-I	0.2		1951-1963
	EBR-II	20		1963-1994
	Fermi 1	66		1963-1972
	SEFOR		20	1969-1972
	Fast Flux Test Facility		400	1980-1993

Table 5. Major experimental, pilot and demonstration fast breeder reactors

Other concepts of fast reactors using lead or lead-bismuth alloys as coolant, thus avoiding safety risks associated with sodium coolant, are selected as promising new projects for Generation IV reactors (Gen. IV International Forum, 2011a). Theoretical resource extension by fast breeder technology is very large, as the energy of dominant isotope of uranium is liberated. Extension is not only by a factor of about 50 coming from conversion of U238, but also from the possibility to use uranium resources too expensive for the present light water reactors with their inefficient use of uranium. It is correct to state that fast breeder reactors present technical option which can remove the resources constraint on any conceivable future nuclear energy strategy. Their deployment depends on economic and safety considerations, such as investment and reprocessing costs and plutonium diversion safety. New concepts in development attempt to preserve attractive safety features, such as low primary pressure, but avoid the use of sodium coolant which burns in contact with water.

3.4 Zonal fuel burning in so called “candle reactor”

Zonal burning concept, respectively, Travelling Wave Reactor (also called “candle reactor”) (Ellis et.al., 2010) is an old idea proposed in 1958 by S. Feinberg (Feinberg, 1958). Recently it was given new attention by several investigators, especially by H. Sekimoto from the Tokyo

Institute of Technology (Sekimoto et.al., 2008). This reactor concept promises very high uranium utilization, about 40% of U238 in fuel, without the need for reprocessing. Needles to say, that would dramatically increase energy obtainable from uranium with very great advantage that reprocessing is not required. Fissile material is burnt and created in situ in the zone that moves through the reactor core. Concept is certainly very attractive, but real perspective is not yet clear. It could be a major advance in the use of nuclear fission energy, but it has not been demonstrated and is still in the early phase of development. Open problems are fuel and other core materials capable to sustain very high burn-up. Clarifications on the initiation of the burning are needed. Attempt to construct a prototype of this reactor type is supported by Bill Gates foundation.

3.5 Accelerator conversion of U238 into plutonium and of Th232 into U233

Electronuclear breeding investigation started early within the US MTA project (1949-1954), initiated by E.Lawrence (Heckrotte, 1977). Although technically successful, project was terminated when new uranium deposits large enough for US nuclear programme were discovered. Number of studies in 70ties dealt with the accelerator production of fissile materials Pu239 or U233, but low cost of uranium and proliferation consideration worked against further development. Concept was recently again taken up by C. Rubbia of CERN. In electronuclear accelerator breeding, particle accelerator is optimized in particle energy and target selection to produce thermal neutrons at minimum energy cost. Using protons in the range of 1000- 1500 MeV or deuterons with twice this value, minimum energy is lost on ionization in the large uranium or thorium target, whilst energetic ions produce neutrons first in spallation reactions and then in fast neutron reactions such as (n,2n) or (n,3n) which further increase number of neutrons of lower energy before they are thermalized and absorbed in fertile materials U238 or Th232. Project studies show that economy of plutonium production requires the proton beams of 200-300 mA corresponding to a beam power of about 200-300 MW. It is believed that extrapolation of present accelerators to such beams would not require new physical development. Accelerator target would in size and power dissipation resemble nuclear reactor core, profiting thereby from the existing reactor technology. Such an accelerator combined with the conventional thermal reactors fed by fertile nuclides produced by accelerator-breeder would present a system producing energy with an input of natural uranium or thorium fuel only. While in principle such hybrid system offers as effective use of natural uranium as a fast breeder reactor, it has an important advantage that fissile material production can be separated in time and location from the energy production. Accelerator and reprocessing installation would parallel enrichment installations, with a difference that the largest part of natural uranium input could be turned into fissile isotopes. Another advantage is that produced fissile materials could be fed into existing proven conventional reactors (Bowman et.al., 1992; Fraser et.al., 1981; Kouts & Steinberg, 1977; Lewis, 1969; Steiberg et al., 1983).

3.6 Conversion of U238 and Th232 by fusion neutrons

Several studies have shown that fusion devices unable to reach positive energy balance required to operate as pure fusion power producer, could still serve as neutron source producing neutrons for conversion of uranium or thorium. With fissile materials produced by neutron irradiation fed into conventional fission reactors, hybrid system of fusion device and fission reactors can produce energy with input of natural uranium or thorium only, as accelerator breeder systems. Many general and economic considerations are similar to those for accelerator breeders, with an advantage of less complexity in case of accelerator system, where the accelerator target technology could use much of reactor core technology. At present development required for accelerator breeders appears less demanding than development of fusion breeder devices (Maniscalco et.al., 1981).

3.7 Perspectives of nuclear fuel utilization improvement

At this moment it is difficult to foresee which, if any, of these ways to utilize the energy of U238 and Th232 will be developed. Molten salt thermal breeder might have the best chance, being one of the Generation IV selections. Second chance could be one of the fast breeder concepts with the coolant more acceptable than sodium. When we look at the technologies that may require more time for development, such as accelerator breeders or fusion –fission hybrids, we should note that time is not a limitation, as with effective burning of U238 nuclear fission energy is a source for the next thousands of years. At that time scale it does not matter whether they are developed in 50 or in 100 years. What is however important is to know that technologies exist which if developed and applied would make nuclear fission an energy source we cannot run out.

Cost of enriched sea extracted uranium determines the upper limit on the costs of any of above concepts for utilization of U238. An essential reduction of seawater uranium extraction cost would consequently reduce the number of economically acceptable concepts out of the list of physically and technically possible concepts presented above, respectively, move them into the more distant future.

4. Projections of long term world nuclear energy demand and nuclear fuel requirements

In order to assess long term sustainability of uranium resources a number of scenarios with different nuclear energy development strategies have been analysed. In the upcoming subsection we first give general assumptions and calculational methodology used in the analysis of all scenarios. We then proceed with detailed description of each particular scenario including specific assumptions and overall calculational results.

4.1 General assumptions and calculational methodology

In all the development strategies, i.e., scenarios, once-through fuel technology has been used. Spent fuel was assumed to be stored in spent fuel casks on controlled sites, enabling possibility of future reprocessing. The year 2010 has been chosen as the starting year for all the scenarios. The initial parameters used are those for the year 2009 and are based on the World Energy Outlook (WEO) 2009 (IEA, 2009) reference scenario data, the joint report by OECD Nuclear Energy Agency and the International Atomic Energy Agency regarding uranium resources (OECD/NEA & IAEA, 2010), and some assumptions based on engineering judgement and experience. These parameters are as follows:

- conventional uranium resources have been used in all scenarios as availability merit; these resources equal to 16.7 million tonnes (OECD/NEA & IAEA, 2010),

- conversion factor addressing the amount of uranium required for production of 1 TWh of electricity equals 25.0 tU/TWh; the factor has been conservatively set based on the analyses of electricity production in nuclear power plants and corresponding uranium demand over the last decade (OECD, 2006; OECD/NEA & IAEA, 2010); the value for the conversion factor has been verified theoretically (Bodansky, 2004),
- conversion factor addressing the mass of plutonium in spent fuel based on energy production is 0.17 tPu/GWye (Bodansky, 2004),
- constant capacity factor for nuclear power plants of 0.88 has been used for the entire investigated period in all scenarios,
- scenarios 2, 3 and 4 are selected in order to see the adequacy of uranium resources for essential contribution to carbon emission reduction, as required by WEO 2009 450 Strategy that would keep temperature increase below 2°C (IEA, 2009). Owing to general safety consideration we assume conventional reactor technology until the end of century and postponement of reprocessing until 2065, respectively 2100. This is also the reason for using conservative parameters for evaluation of uranium consumption. Scenario 1 is a low growth scenario which would not contribute essentially to carbon emission reduction.

4.2 Scenario 1 – Low growth scenario

A scenario of low nuclear capacity growth is a typical scenario showing that for a small share of nuclear energy in the total world production of energy, resources are not a limiting factor. This scenario assumes moderate growth strategy of 0.6% per year for the period 2011 – 2025, and 1.3% after the year 2025, following the 450 Policy Strategy of WEO 2009 (IEA, 2009). The scenario aims at preserving the share of nuclear energy in the total energy production. Although the present growth of total energy production and consumption is higher, we do not consider it appropriate for the longer periods in question. The investigated period is the entire 21st century, with special attention placed on the year 2065, which is later used as a milestone in scenario 2 and scenario 3. The results are given in Table 6.

Cumulative uranium requirements up to the year 2065 would be approximately 5.4 million tonnes, while for the entire 21st century cumulative requirements would reach 11.3 million tonnes. By the year 2100 installed nuclear capacity would reach 1080 GWe producing more than 8,000 TWh of electricity per year. It is also interesting to notice that cumulative mass of plutonium in spent fuel by the year 2100 would be slightly below 9,000 tonnes. If the same level of nuclear capacity increase would be used beyond the year 2100, the conventional uranium resources of 16.7 million tonnes would be exhausted by the year 2123.

4.3 Scenario 2 – Exponential high growth scenario

Exponential high growth scenario is determined by asking for the maximum nuclear build-up that can be reached by the year 2065, compatible with present estimate of uranium resources and their use with once-through nuclear technology, i.e. without reprocessing. Exponential growth with annual increase of 2.35% is used for the initial period 2011 – 2025.

The aim of the scenario analysis is to deduce the maximum growth, i.e., the maximum nuclear build-up that can be achieved throughout the period 2026 – 2065, with the assumption that at the end of the period the current uranium resources of 16.7 million tonnes would be exhausted. The year 2026 has been chosen as the starting year for rapid nuclear build-up based on the estimate of present status of nuclear industry and the time needed to prepare such a massive undertaking. The results are given in Table 7.

Year	Nuclear capacity (GWe)	Annual electricity production [TWh]	Annual U requirements (ktU)	Cumulative U requirements (ktU)	Annual mass of Pu in spent fuel (tPu)	Cumulative mass of Pu in spent fuel (tPu)
2010	375	2,890	72	72	56	56
2015	386	2,978	74	440	58	342
2020	398	3,068	77	819	60	636
2025	410	3,161	79	1,210	61	939
2030	437	3,372	84	1,620	65	1,258
2035	467	3,597	90	2,059	70	1,598
2040	498	3,837	96	2,526	74	1,961
2045	531	4,093	102	3,025	79	2,348
2050	566	4,366	109	3,557	85	2,761
2055	604	4,658	116	4,124	90	3,201
2060	644	4,968	124	4,729	96	3,671
2065	687	5,300	132	5,375	103	4,172
2070	733	5,653	141	6,064	110	4,707
2080	834	6,433	161	7,582	125	5,886
2090	950	7,320	183	9,310	142	7,227
2100	1,080	8,329	208	11,276	162	8,753

Table 6. Scenario 1 (low growth scenario) results

Under the condition of uranium resources exhaustion by the year 2065, the maximum possible annual growth rate for the period 2025 – 2065 is 5.7%. Thus, by the year 2065 installed nuclear capacity would reach 4,878 GWe producing more than 37,000 TWh of electricity in that year. Under the scenario terms, the maximum increase of nuclear capacity is observed during the last year of examined period and equals 263 GWe. It is also interesting to notice that cumulative mass of plutonium in spent fuel until the year 2065 would slightly exceed 13,000 tonnes. Very high contribution, over 50%, to the carbon emission reduction as required by WEO 2009 450 Strategy would be reached by 2065.

Based on previous discussion on long-term perspective of nuclear fuel resources presented in subsection 2.3, one can assume that the current estimate of 16.7 million tonnes of conventional uranium resources is likely to increase in the next 50 years. Therefore, it would be interesting to see the uranium requirements for the entire 21st century. A number of development strategies for the period 2066-2100 could be taken into account. However, we limit our investigation on a simple one, foreseeing constant nuclear capacity that equals the one reached by the year 2065 - 4,878 GWe. The results are also given in Table 7.

Cumulative uranium requirements for the period 2066-2100 would amount to approximately 33 million tonnes. If reprocessing of spent fuel and plutonium cycle (MOX fuel) is envisioned as possible after the year 2065 (WNA, 2011a), then cumulative mass of plutonium in spent fuel up to the year 2098 would amount to slightly more than 37 thousand tonnes. The year 2098 has been taken as final for plutonium accumulation to enable reprocessing of spent fuel and MOX production. Assuming that 70% of accumulated plutonium in spent fuel is fissile (Bodansky, 2004) reduction of uranium requirements in the amount of 5.7 million tonnes could be expected.

Year	Nuclear capacity (GWe)	Annual electricity production [TWh]	Annual U requirements (ktU)	Cumulative U requirements (ktU)	Annual mass of Pu in spent fuel (tPu)	Cumulative mass of Pu in spent fuel (tPu)
2010	375	2,890	72	72	56	56
2015	421	3,246	81	460	63	357
2020	473	3,646	91	895	71	695
2025	531	4,095	102	1,384	79	1,074
2030	701	5,403	135	1,990	105	1,545
2035	925	7,128	178	2,790	138	2,166
2040	1,220	9,405	235	3,846	183	2,985
2045	1,610	12,409	310	5,238	241	4,066
2050	2,124	16,372	409	7,076	318	5,492
2055	2,802	21,601	540	9,500	419	7,374
2060	3,697	28,500	712	12,698	553	9,857
2065	4,878	37,603	940	16,918	730	13,133
2070	4,878	37,603	940	21,618	730	16,781
2075	4,878	37,603	940	26,319	730	20,430
2080	4,878	37,603	940	31,019	730	24,079
2085	4,878	37,603	940	35,719	730	27,727
2090	4,878	37,603	940	40,420	730	31,376
2095	4,878	37,603	940	45,120	730	35,025
2100	4,878	37,603	940	49,821	730	38,673

Table 7. Scenario 2 (exponential high growth scenario) results

4.4 Scenario 3 – Linear high growth scenario

As in the previous scenario, a scenario of linear high growth is determined by asking for the maximum nuclear build-up that can be reached by the year 2065 with the assumption that current conventional uranium resources would be exhausted by the same year. However opposed to scenario 2, it assumes linear growth rate. Also for the period 2011-2025 linear growth rate is envisioned similar to the WEO 2009 reference scenario (IEA, 2009) resulting in 459 GWe of installed nuclear capacity in the year 2025. Annual increase in nuclear capacity for the period 2011 – 2025 is approximately 5.6 GWe. The results of scenario 3 analysis are given in Table 8.

Under the same conditions as in the previous scenario (current uranium resources exhaustion by the year 2065), the maximum possible annual increase of installed nuclear capacity for the period 2025 – 2065 is 75.5 GWe. Thus, by the year 2065 installed nuclear capacity would reach 3,479 GWe producing almost 27,000 TWh of electricity per year. Compared to previous scenario, scenario 3 results in larger penetration of new nuclear capacity at the beginning of investigated period. This is an advantage from the carbon emission reduction considerations. For example, scenario 2 projects 30 GWe of new nuclear capacity for the year 2026, as opposed to 75.5 GWe of scenario 3. Graphical representation of annual increase in nuclear capacity for scenario 2 and scenario 3 is given in Fig. 3. Cumulative mass of plutonium in spent fuel until the year 2065 would slightly exceed 13,000 tonnes just as in the case of the previous scenario.

As well as for scenario 2, extension of scenario 3 up to the year 2100 has been analysed, assuming nuclear capacity of 3,479 GWe for the period 2066-2100. The results of extended scenario 3 are also given in Table 8.

Year	Nuclear capacity (GWe)	Annual electricity production [TWh]	Annual U requirements (ktU)	Cumulative U requirements (ktU)	Annual mass of Pu in spent fuel (tPu)	Cumulative mass of Pu in spent fuel (tPu)
2010	375	2,890	72	72	56	56
2015	403	3,106	78	450	60	350
2020	431	3,322	83	854	65	665
2025	459	3,538	88	1,286	69	1,001
2030	836	6,448	161	1,946	125	1,515
2035	1,214	9,358	234	2,971	182	2,312
2040	1,591	12,269	307	4,359	239	3,392
2045	1,969	15,179	379	6,110	295	4,756
2050	2,346	18,089	452	8,226	352	6,403
2055	2,724	20,999	525	10,705	409	8,332
2060	3,101	23,909	598	13,548	465	10,545
2065	3,479	26,819	670	16,755	522	13,041
2070	3,479	26,819	670	20,108	522	15,650
2075	3,479	26,819	670	23,460	522	18,260
2080	3,479	26,819	670	26,812	522	20,869
2085	3,479	26,819	670	30,165	522	23,478
2090	3,479	26,819	670	33,517	522	26,087
2095	3,479	26,819	670	36,869	522	28,697
2100	3,479	26,819	670	40,222	522	31,306

Table 8. Scenario 3 (linear high growth scenario) results

Cumulative uranium requirements for the period 2066-2100 would amount to approximately 23.5 million tonnes. The cumulative mass of plutonium in spent fuel up to the year 2098 would amount to 30.2 thousand tonnes. If reprocessing of spent fuel and plutonium cycle (MOX fuel) is envisioned as possible after the year 2065, and using the same assumption as in the previous scenario a reduction of uranium requirements in the amount of 4.6 million tonnes would be expected.

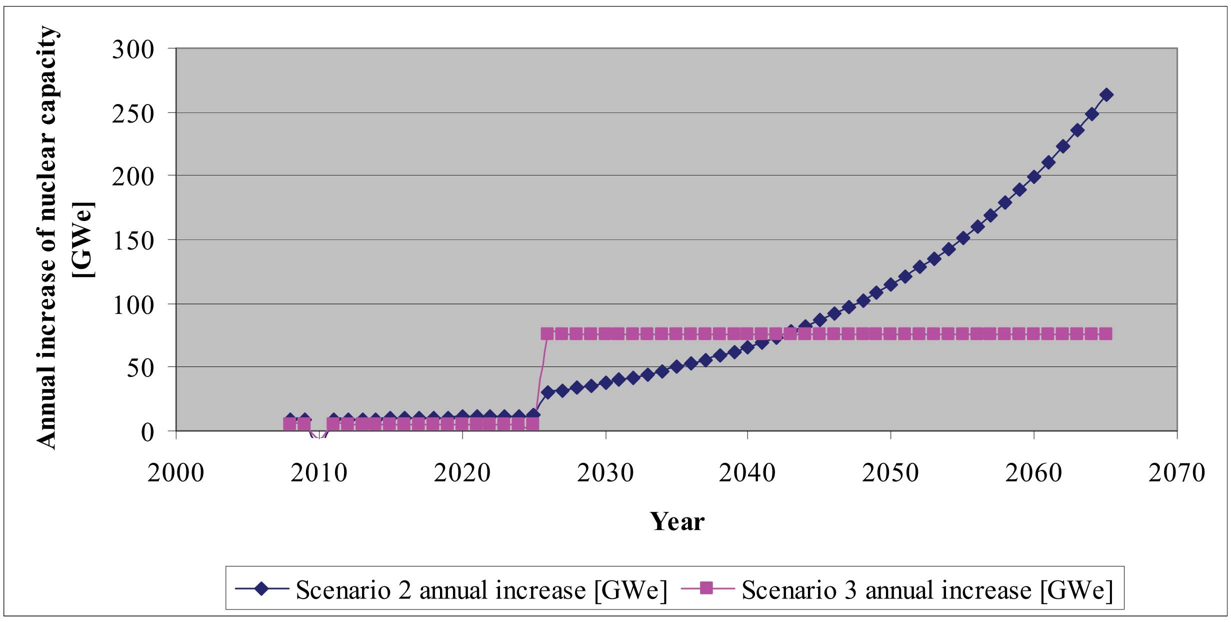

Fig. 3. Annual increase in nuclear capacity for scenario 2 and scenario 3

4.5 Scenario 4 – An intermediate scenario

Scenarios 2 and 3, i.e., high growth scenarios, provide illustration on maximum growth of nuclear capacities possible under stated resources constraint. Scenario 4 illustrates a less demanding nuclear build-up strategy that would replace all coal power plants without Carbon Capture and Storage (CCS) system, with nuclear power plants during the 2026-2065 period. Unlike scenario 1 this scenario would still give important contribution to carbon emission reduction, albeit not as high as the scenarios 2 and 3. It is assumed that all new coal power plants build after the year 2025 would have CCS installations. Linear replacement dynamics starting in the year 2026 is assumed without specifying the exact dates of coal power plant replacement. As in the previous scenario linear growth rate is envisioned for the period 2011-2025, similar to the WEO 2009 reference scenario (IEA, 2009), resulting in 459 GWe of installed nuclear capacity in the year 2025. Same WEO 2009 reference scenario (IEA, 2009) states that electricity production in coal power plants would be 13,387 TWh in the year 2025. With availability factor of 0.88, installed nuclear capacity of 1,736 GWe would be required to replace coal power plants electricity production. The results of scenario 4 analysis are given in Table 9.

Goal of all non-CCS coal power plants replacement throughout the period 2026-2065 would require an annual increase of nuclear capacity in the amount of 43.4 GWe. The total installed nuclear power by the year 2065 would reach 2,195 GWe with electricity production of almost 17,000 TWh. Cumulative mass of plutonium in spent fuel until the year 2065 would slightly exceed 9,000 tonnes which is rather lower than in previous two scenarios.

As in the previous two scenarios, extension of scenario 4 up to the year 2100 has been analysed assuming nuclear capacity of 2195 GWe for the period 2066-2100. The results of extended scenario 4 are also given in Table 9.

Intermediate nuclear growth envisioned in scenario 4 results in cumulative uranium requirements up to the year 2065 in the amount of slightly less than 12 million tonnes. The current conventional uranium resources would be exhausted by the year 2077. Cumulative uranium requirements for the period 2078-2100 would amount to approximately 9.7 million tonnes. If reprocessing of spent fuel and plutonium cycle (MOX fuel) is envisioned as possible after the year 2065, then cumulative mass of plutonium in spent fuel up to the year 2098 would amount to 19.9 thousand tonnes resulting in possible reduction of uranium requirements in the amount of 3.1 million tonnes.

Year	Nuclear capacity (GWe)	Annual electricity production [TWh]	Annual U requirements (ktU)	Cumulative U requirements (ktU)	Annual mass of Pu in spent fuel (tPu)	Cumulative mass of Pu in spent fuel (tPu)
2010	375	2,890	72	72	56	56
2015	403	3,106	78	450	60	349
2020	431	3,322	83	854	64	663
2025	459	3,538	88	1,286	69	998
2030	676	5,211	130	1,853	101	1,439
2035	893	6,884	172	2,630	134	2,042
2040	1,110	8,557	214	3,616	166	2,807
2045	1,327	10,230	256	4,811	199	3,735
2050	1,544	11,902	298	6,215	231	4,825
2055	1,761	13,575	339	7,829	263	6,077
2060	1,978	15,248	381	9,651	296	7,492
2065	2,195	16,921	423	11,683	328	9,069
2070	2,195	16,921	423	13,798	328	10,710
2075	2,195	16,921	423	15,913	328	12,352
2080	2,195	16,921	423	18,028	328	13,994
2085	2,195	16,921	423	20,143	328	15,636
2090	2,195	16,921	423	22,258	328	17,278
2095	2,195	16,921	423	24,373	328	18,920
2100	2,195	16,921	423	26,488	328	20,562

Table 9. Scenario 4 (intermediate growth scenario) results

5. Discussion on the long term sustainability of nuclear resources

As we stated introductory, energy that can be released by nuclear fission from uranium or thorium is not determined, or not essentially determined, by the quantity of resources. This is an essential difference to note when comparing nuclear with fossil fuel resources. On the other hand physical quantities of resources are, similarly as for fossil fuels, defined by extraction costs and by accepted criteria for categorization and estimates of deposits. Energy that can be liberated from unit mass of natural uranium varies by a large factor depending on the reactor and fuel cycle technology. Economic criteria on uranium deposits are consequently much more dependent on the energy conversion technology than in the fossil energy use. If the technology applied releases much more energy per unit mass than the present conventional reactors, then more expensive uranium or thorium deposits can be economically exploited. However our approach on the nuclear technologies to be used in this century is conservative. Therefore, our first interest is to see how far we can go with conventional, or essentially conventional nuclear technology. When considering present and future nuclear technologies which determine the requirements we must not take a narrow technical view on the possible fuel and reactor technologies. Development of nuclear safety is a slow process, reactors built in the nuclear boom in the late seventies and early eighties of the last century are still running, albeit approaching retirement. Although there are some 14 000 years of reactor experience, change of generations is a slow process, and such is the rate of change in basic reactor concepts. As the recent accidents at Fukushima show there is still a room for improvement even on the dominant line of light water reactors operating in a once-through fuel cycle. This is a reason why we estimate the uranium requirement in this century without introduction of breeder reactors. Also, we do not foresee before the end of century any major contribution of other technologies for extension of uranium or thorium utilization (Section 3). Our further basic assumption is on the role that nuclear fission should play in the critical period of about 50 years from now before wind, solar, nuclear fusion and CCS may contribute essential part of energy production. Nuclear fission energy is a proven, developed and economical source of carbon free energy. It is very difficult to see that the internationally accepted target to keep the mean global temperature increase below 2 °C could be achieved without the use of nuclear energy. Therefore in estimating the future needs of uranium we consider such deployments of nuclear power as can give an essential contribution to reduction of carbon emission. Often shown strategies with low growth, such as scenario 1 included in previous Section 4, result in assurances about the long life of resources, but are pointless for the purpose of climate control. For our purpose relevant are strategies 2, 3, and 4 of Section 4.

These strategies are an extension of the strategies we investigated earlier (Knapp et al., 2010) with the aim to determine what could be maximum contribution of nuclear energy in reduction of carbon emission down from the projected WEO 2009 Reference scenario to the sustainable WEO 450 scenario limiting the temperature increase to 2°C. Strategies were constrained to the use of proven conventional reactors operating in the once-through nuclear fuel cycle, without fuel reprocessing and plutonium recycle. Maximum nuclear contribution was obtained in strategies 2 and 3 by further assumption that total conventional uranium resources estimated in 2009 Red Book be consumed by the year 2065. The point of the study was not in proposing any specific growth strategy, but rather to see whether with conventional reactor technology, without spent fuel reprocessing, nuclear energy can essentially contribute to the carbon emission reduction. An argument for selection of the year 2065 for the final year of nuclear build-up is essentially derived from the status of nuclear and renewable technologies, as well as CCS and fusion prospects and their perspective for large contributions in carbon emission reduction. Under these constraints maximum annual nuclear capacity growth for the linear growth strategy (scenario 3), between the years 2025 and 2065 was 75.5 GW, reaching installed nuclear power of 3479 GW in 2065. By that year nuclear contribution to the required GreenHouse Gasses (GHG) emission reduction comes to the value of 39.6% of the WEO 450 Strategy requirements (Knapp et al., 2010). This is a very serious contribution which still leaves large space of remaining about 60%, respectively of 38.4 GtCO2–eq reduction to be achieved by renewable energy sources, respectively, by energy efficiency and other ways of carbon emission reduction. If consumption of total uranium resources, as estimated in 2009, was required to achieve a serious contribution of nuclear energy to carbon emission control by 2065, should one then conclude that nuclear energy cannot continue in production of carbon free energy with the same share in total energy production? This is question certainly very relevant for judgment on sufficiency of uranium resources and we try to answer it in Section 4. To obtain a quantitative base for this we continued our scenarios 2, 3, and 4 from the year 2065 up to 2100 on the power levels reached by the year 2065, i.e. with powers of 4878 GW, 3479 GW, and 2195 GW for strategies 2, 3, and 4, respectively. In view of the expected slow growth of total energy consumption in the last decades of the century the contributions of all three strategies to carbon emission reduction will remain substantial, not much below their values in 2065. For all three strategies we have calculated cumulative uranium requirements from 2010 through to 2100 without reprocessing and with reprocessing after 2065. Assumption of study was to postpone fuel reprocessing as late as 2065 in order to give sufficient time for development of all political, institutional and technical condition for safe use of plutonium. The required quantities of uranium without reprocessing are 49.8 Mt, 40.2 Mt, and 26.5 Mt for strategies 2, 3, and 4, respectively. The required quantities of uranium with reprocessing after 2065 are 44.1 Mt, 34.3 Mt, and 23.4 Mt for strategies 2, 3, and 4, respectively. The estimated uranium requirements until 2100 are upper limits as they are obtained by conservative assumption on the efficiency of uranium use, i.e. by assuming operation of present technology conventional reactors.

Even for the highest nuclear capacity growth of scenario 2 the uranium requirements are less than 50 Mt, the uranium resources estimated by simple crustal model.

For scenario 3, assuming plutonium recycle after 2065, the conservative estimate, based on the use of conventional reactors and ignoring reductions by the more efficient Generation 4 reactors, ends with uranium requirements on the level of 35.6 million tonnes up to the year 2100. In other words, keeping the present proven reactor technology, with plutonium recycle postponed to 2065, one could go on with a nuclear share of about one third in the total energy production until 2100 with approximately double uranium resources as estimated in 2009. Our figure without reprocessing until 2100 is about 13% higher and it amounts 40.2 Mt. While we can expect the conditions for reprocessing to exist by 2065, we can say that even the postponement of reprocessing until 2100 for strategy 3 with a very large contribution of carbon free energy results in still acceptable requirements. This is certainly so for the intermediate Strategy 4, which still contributes with about one quarter to required emission reduction, while the uranium requirements are lower.

Whether the introduction of reprocessing after 2065 will be necessary will depend on many future developments, such as the improvement of conventional nuclear technology, progress in fusion and CCS technology, rate of deployment of renewable resources, and of course, on the rate of increase of uranium resources. About this we cannot speculate. Also, we do not want to discuss in this place the wisdom or the feasibility of giving up nuclear energy in view of the enormous tasks world is facing to control the climate changes by GHG emissions. What we do want to show is that until the end of century uranium resources are not a limiting factor for a large nuclear contribution on the level of 3479 GW approximately, i.e. on the level of one third of total energy production, without introduction of such technologies as fast breeder reactors. That should be sufficient for a reasonable assurance that a strategy such as WEO 450 could be achieved, provided, of course, that renewable source and other ways of GHG emission control contribute their large shares. After 2065 there could be a welcome contribution from CCS installation, and, less likely, from fusion. If these developments fail, our estimates show that continued share of nuclear energy could be supported by conventional reactor technologies up to the end of century. Large scale introduction of fast breeders after 2100 would make the issue of uranium or thorium resources irrelevant for future energy production. Needless to say, in that case the uranium from the seawater would open as economically acceptable and for all practical purposes inexhaustible uranium source.

However, we do not want to overplay these future possibilities. It is not enough to show that nuclear energy is sustainable. This is easily done by assuming an early introduction of breeder reactors. However, in democratic societies nuclear energy must also be acceptable to most citizens. Nuclear energy must prove itself to be evidently safe, technically and politically. That is why it would be preferable to continue with proven technology till about the end of century. We show that possible from the point of resources. Many safety improvements were applied on the light water reactors after the Three Mile Island accident in 1979. There will be some lessons after Fukushima 2011 accidents. Applied, they will contribute further to the safety of present reactor line. Rather than changing basic technology too soon, it may be wiser to demonstrate several decades of safe and reliable operation of present one. That would be a good preparation for later introduction of new technologies, such as breeders. This is not a long delay, considering that with new technologies to use U238 and Th232 nuclear energy can serve humanity for thousands of years.

6. Conclusions

Under the long term sustainability of nuclear resources we understand the capability to support long term large share of nuclear energy (of about one third) in total energy production and in reduction of carbon emission. We determined the uranium requirement for corresponding nuclear strategies to 2065 and to the end of century. In view of our survey of non-conventional uranium resources with potential to substantially expand conventional uranium resources, as well as expected increase of conventional resources estimates relative to their 2009 values, and looking at the results of above presented nuclear strategies 2,3 and 4, we feel justified to conclude that, after nuclear build-up in the period 2025-2065, nuclear energy share on the achieved level of about 3479 GW, respectively about one third in the total energy production, can be sustained until the end of century using only proven conventional reactor technology or with introduction of plutonium recycle after 2065. Our conservative estimate indicate, that in later case about 35.6 million tonnes of uranium would be required by 2100 in that case. Postponing the spent fuel reprocessing until the end of century would increase uranium requirement to about 40.2 million tonnes.

Technologies and methods for improvement of nuclear fuel utilization have been considered. Even though some of these technologies are developed and proven technically viable, substantial implementations of these technologies are not expected in this century. While some effects on reduction of uranium requirements before the end of century may be possible, our aim for conservative estimates does not take them into account.

Looking to the end of century we note that based on a geochemistry model the total amount of uranium recoverable at price of 180 USD/kg U is estimated to 50 million tonnes.

On the technology side, large scale introduction of fast breeders after 2100 would make the issue of uranium or thorium resources irrelevant for future energy production.

Shorter and long term sustainability potential of nuclear fuel resources is enhanced by expected extraction of uranium from phosphates and seawater.

Finally, it may be concluded that nuclear fuel resources will not be a constraint for long term nuclear power development, even if the use of nuclear power is aggressively expanded.

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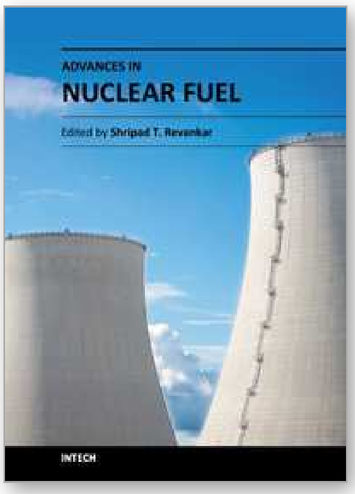

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Worldwide there are more than 430 nuclear power plants operating and more plants are being constructed or planned for construction. For nuclear power to be sustainable the nuclear fuel must be sustainable and there should be adequate nuclear fuel waste management program. Continuous technological advances will lead towards sustainable nuclear fuel through closed fuel cycles and advance fuel development. This focuses on challenges and issues that need to be addressed for better performance and safety of nuclear fuel in nuclear plants. These focused areas are on development of high conductivity new fuels, radiation induced corrosion, fuel behavior during abnormal events in reactor, and decontamination of radioactive material.