Nuclear Science
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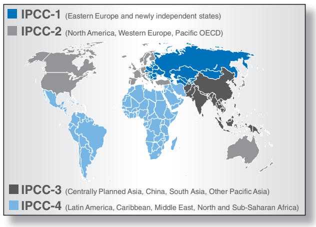
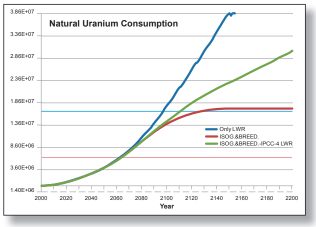
Transition Towards a Sustainable Nuclear Fuel Cycle





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Nuclear Science

Transition Towards a Sustainable Nuclear Fuel Cycle

NEA No. 7133

NUCLEAR ENERGY AGENCY
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Foreword

Under the auspices of the NEA Nuclear Science Committee (NSC), the Working Party on Scientific Issues of the Fuel Cycle (WPFC) was established to co-ordinate scientific activities regarding various existing and advanced nuclear fuel cycles, including advanced reactor systems, associated chemistry and flow sheets, development and performance of fuel and materials, and accelerators and spallation targets. The WPFC has different expert groups to cover a wide range of scientific fields concerning the nuclear fuel cycle.

The WPFC Expert Group on Advanced Fuel Cycle Scenarios was created in 2010, replacing the WPFC Expert Group on Fuel Cycle Transition Scenario Studies, to assemble, organise and understand the scientific issues of advanced fuel cycles; and to provide a framework for assessing specific national needs related to the implementation of advanced fuel cycles.

This report analyses global nuclear energy demand scenarios in the context of a transition from current technologies to fast reactors. The study mainly focuses on uranium resource demand; nuclear reactor construction rates; radioactive waste management; used fuel discharged as a function of time; composition and radiotoxicity; and infrastructure requirements as a function of time.

Acknowledgements

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Executive summary

To support the evaluation of R&D needs and relevant technology requirements for future nuclear fuel cycles, the OECD/NEA WPFC Expert Group on Advanced Fuel Cycle Scenarios was created in 2010, replacing the WPFC Expert Group on Fuel Cycle Transition Scenario Studies (1) to assemble, organise and understand the scientific issues of advanced fuel cycles and (2) to provide a framework for assessing specific national needs related to the implementation of advanced fuel cycles.

In this framework, a simulation of world transition scenarios towards possible future fuel cycles with fast reactors has been performed, using both a homogeneous and a heterogeneous approach involving different world regions. In fact, it has been found that a crucial feature of any world scenario study is to provide not only trends for an idealised "homogeneous" description of the world, but also trends for different regions in the world, selected with simple criteria (mostly of geographical type), in order to apply different hypotheses to energy demand growth, different fuel cycle strategies and different reactor types implementation in the different regions.

This approach was an attempt to avoid focusing on selected countries, in particular on those where no new spectacular energy demand growth is expected, but to provide trends and conclusions that account for the features of countries that will be major future players in the world's energy development.

The heterogeneous approach considered a subdivision of the world in four main macro-regions (where countries have been grouped together according to their economic development dynamics). An original global electricity production envelope was used in simulations and a specific regional energy share was defined. In the regional approach two different fuel cycles were analysed: a once-through LWR cycle was used as the reference and a transition to fast reactor closed cycle to enable a better management of resources and minimisation of waste.

In this respect, it is considered that the potential future scarcity of uranium resources is not at all unreasonable, but it is a very serious perspective for the regions of the world where the energy demand growth is and will very probably continue to be significant with the use of nuclear energy to meet at least partially that demand. In fact, despite the seriousness of the recent Fukushima Daiichi accident, only a few countries (essentially in the OECD region) have reacted with an abrupt decision to phase out nuclear power. Most countries, where the energy demand growth corresponds to an urgent need to achieve widely improved living standards, have launched or completed extensive reviews of their nuclear programmes, but are also continuing with ongoing construction projects.

The results of this study are very much related to the hypotheses made, in particular in terms of energy demand growth. However, some general trends seem to be of a general value and can motivate further studies.

It was confirmed in this investigation that a rapid development of fast reactors, especially in areas with expanding economies and strong energy demand growth, is essential for nuclear energy sustainability, for saving natural uranium resources worldwide and for reducing high-level waste generation requiring disposal. A key parameter is the fast reactor doubling time which has to be chosen appropriately in order to meet energy requirements.

In the case of an open cycle, a potential increase in pressure on the uranium market could be expected towards the end of the current century. Moreover, the increase in mining needs of unequally distributed resources can be a factor of uncertainty with an impact potentially even more important of uranium cost considerations.

It would, however, be a very significant challenge to develop suitable fuel cycle infrastructure especially in the world regions that presently have a limited number of (or no) nuclear power plants. In fact, the needed fuel fabrication and spent fuel reprocessing capacities should increase by at least one order of magnitude over the next decades.

This study should be considered as a preliminary attempt to associate quantified impacts with foreseeable nuclear energy development. The report also gives some guidelines for performing future studies to account for a wider range of hypotheses on the energy demand growth, different hypotheses on uranium (and thorium, although not considered in the present study) resource availability, and the different types of reactors to be deployed (e.g. high conversion ratio light water reactors).

1. Introduction

Today 440 nuclear reactors are operational and 64 are under construction, providing a significant share of global energy production (especially in developed regions) and avoiding the emission into the atmosphere of significant amounts of pollutants and greenhouse gases [1]. Many studies have proved moreover that nuclear energy is a cost-competitive and reliable energy source [2]. Despite the recent Fukushima Daiichi accident, a significant increase in nuclear energy demand is still expected in the next few years and consequently some important issues about uranium resources and infrastructure availability are likely to result, within a framework of enhanced safety requirements.

It is widely accepted that the implications of a world transition from current open (or partially closed) fuel cycles (FC) towards future sustainable closed cycles implementing partitioning and transmutation (P&T) still require intensive investigation, which should take into account various scenarios.

To support evaluation of R&D needs and relevant technology requirements, the NEA/OECD WPFC Expert Group on Fuel Cycle Transition Scenarios Studies has been established. The tasks of the expert group were to assemble and organise institutional, technical and economic information critical to the understanding of the issues involved in transitioning to a long-term sustainable nuclear fuel cycle and to provide a framework for assessing specific national needs related to that transition.

Different options were proposed and many studies have been performed worldwide, which will be described briefly in the next paragraph; however, the present work has focused on a limited number of parameters in order to point out major trends and issues. For this reason, some options were not treated in the present document, such as thorium resources exploitation, despite its potential and plans for future utilisation in some countries, such as India for example [3, 4].

Since it is likely that any medium-term development of nuclear energy, in particular in countries in a phase of initial deployment of the nuclear option, will be based on the implementation of third generation reactors (e.g. third generation PWRs, since this is the LWR on which the study focused), reference scenarios have been investigated based on those reactors and once-through fuel cycles. The potential resulting stress on uranium resources, in particular in countries with the fastest growing energy demand, has suggested investigating the impact of the gradual introduction of advanced fuel cycles based on closed cycles and fast neutron reactors.

It has been found that a crucial feature of any world scenario study is to provide not only trends for an idealised “homogeneous” description of the world, but also trends for different regions in the world. These regions may be selected using rather simple criteria (mostly of geographical type), in order to apply different hypotheses to energy demand growth, fuel cycle strategies and the implementation of varying reactor types for the different regions.

This approach was an attempt to avoid focusing on selected countries, in particular on those where no new spectacular energy demand growth is expected, but instead to provide trends and conclusions that account for the features of countries that will be major players in world energy development in the future.

2. Ongoing studies and hypotheses for the present study

2.1. Recent studies

According to international studies on nuclear energy development e.g. [5], the main concerns are related to security of fuel supply (i.e. the long-term availability of resources) and spent fuel management. For this reason a rational approach towards these issues has to be considered and implemented worldwide. Some dedicated studies have been published, which deal with resource optimisation and provide general trends and indications about the date of a possible uranium shortage (or steep cost increase) vs. adopted energy policies and provide some proposals to be adopted in order to avoid possible shortages or market stresses.

In order to investigate in detail the potential contribution of nuclear energy to global energy demand, the IAEA proposed an activity [5] within the INPRO project (International Project on Innovative Nuclear Reactors and Fuel Cycles), in which 32 IAEA member states participate. The study took into consideration resources, reactor types and three different nuclear energy projections: namely low, high and moderate growth rates scenarios. The three considered cases are quite similar until 2030, after which big differences start to be evident, up to a factor of 4 at the end of the present century.

The INPRO study considers thermal spectrum technologies predominant until 2100, assuming that during the next 20 years present light water reactors (LWRs) will be replaced with Generation III + machines (with a 60-year lifetime). Generation IV systems were also investigated, assuming their introduction from 2050. Natural resource exchange between the world regions was assumed, but a restriction due to proliferation issues was assumed concerning enriched uranium and reprocessed materials. Simulation results for the low growth energy scenario indicate that conventional resources will have run out by the end of the present century and a spent fuel (SF) inventory of 1.6 million tonnes (containing ~23 000 tonnes of plutonium) will have to be managed.[1] Therefore, open cycles are not completely sustainable and fast reactor systems adopting closed cycles would be needed, allowing moreover a sensible uranium saving (30-50%) [5].

If a moderate growth energy scenario is assumed, fast growing regions would be forced to develop fast reactors (FR) in order to guarantee fuel supplies. Different breeding ratios (BR) were compared (BR equal to 1.4 and 1.6). In any case, the total uranium resource limit (ca. 40 Mt considering conventional and unconventional resources [17], [18]) will be reached at the end of the present century. Considerable effort is required in order to cope with infrastructure requirements [5].

The high nuclear energy demand scenario requires the adoption of strong breeder reactors (BR ca. 1.6) and the exploitation of thorium resources. It allows a consumption of ca. 20 Mt of uranium at the end of the present century, requiring the use of unconventional resources.

In addition to these main projects other studies are developed worldwide, e.g. [6] [7] in order to contribute to the debate.

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[1] This SF amount corresponds to ca. 20-30 repositories of 70 000 tonnes each.

At CEA, France (*Commissariat à l'énergie atomique et aux énergies alternatives*), scenarios were developed for analysing the transition from Generation II to Generation IV reactors [6]. Different hypotheses about nuclear energy demands were assumed and two cases for FR introduction were considered: a) 20% of the FRs fleet development and b) as rapid as possible FR introduction, according to fissile material available. Results confirm that a once-through cycle is not sustainable and that natural resources will be exhausted at around the middle of the next century; conventional resources will be exhausted by the end of the present century. One proposal was to reduce the burn-up of PWR fuel in order to improve the quality of the produced plutonium, which will subsequently improve the breeding characteristics of fast reactors.

EDF (*Électricité de France*) has also investigated these aspects e.g. [7]. Three different FRs introduction scenarios were assumed, with different introduction dates (from 2030 to 2050). Various options were considered: 1) only pressurised water reactors (PWR), 2) PWR and high-temperature gas-cooled reactors (HTGR), and 3) PWR with MOX fuelled FR (initially loaded with enriched uranium, in order to simplify hypotheses on reprocessing facilities development). The study confirms that PWR- and HTGR-based scenarios are not sustainable from both resource availability and waste production points of view. The cumulative uranium consumption by the middle of the next century would exceed total resources and moreover ca. 70 repositories of about 70 000 tonnes capacity[2] would be required worldwide. The adoption of FRs should improve the scenario, both in terms of natural uranium resources savings and also minor actinides (MA) recycling by the stabilisation of transuranic (TRU) isotopes. The required infrastructure issues would be relevant.

2.2. Nuclear energy demand adopted for the world study

The main constraints applied in this world transition scenario analysis are: the availability of natural uranium resources (ca. 40 Mt according to estimates including unconventional resources [17] [18]), the nuclear generation capacity growth rate (considering global and regional trends) and the type of reactors considered in a transition scenario (thermal, fast self-sustaining or breeder systems).

A short summary of the available data concerning the nuclear capacity growth rates (suitable for both the homogeneous and the heterogeneous studies), is presented here. The analysis of the resource availability and the hypothesis concerning the reactor types adopted in the study are presented in Sections 2.3 and 2.4.

As indicated by [5] [6] [7], the nuclear energy envelopes (and relative regional share) can strongly influence the results of the study in terms of resource shortage and cumulative waste produced.

For the present activity, the data available in the literature have been adopted as the development of energy projections is beyond the scope of this study.

In fact, several heterogeneous parameters, for example, population and economy growth rates, energy policy choices, use of land, analysis of the technological level of a country and their inter-connections have to be taken into account when determining the energy trends.

The data available have been analysed underlining some unrealistic behaviours (total values and relative trends) as shown in Sections 2.2.1-2.2.3.

Suitable nuclear energy envelopes for the world scenario studies (for both the homogenous and heterogeneous approaches) have been selected and adopted (see Section 2.2.4). In particular, for the homogeneous study, the total nuclear energy

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[2] 70 000 tonnes corresponds to the Yucca Mountain capacity.

envelope provided by the Intergovernmental Panel on Climate Change (IPCC – namely, the B2-MiniCAM scenario) has been adopted. The same total envelope, but re-scaled to a more realistic regional subdivision,[3] has been applied to the heterogeneous study (see Section 2.2.4).

2.2.1. Analysis of nuclear energy growth scenarios from available literature

The data available in the literature can be divided into two groups according to the time periods considered. For the long-term period (up to 2100) only IIASA [8] and IPCC [9] provide world and regional energy trends, while short-term (up to 2030-2050) data are also provided by the IEA [10], the IAEA [11] and by the Nuclear Energy Agency (NEA) [12].

The short-term projections, updated almost every year, are more representative of the energy strategy adopted by the countries and of the economic situation (i.e. they are tuned dynamically with respect to the significant economic changes). These data can provide a useful basis for comparison for the long-term projections (i.e. a check of the starting point), but their extrapolation up until 2100 is not reasonable.

The long-term projections are established on the basis of a few selected driving forces: the population growth rate (at world and regional levels), economic aspects and the technical solutions adopted for the energy production (renewable, nuclear or coal-fired). These data are not representative of country-specific situations but they provide reasonable general trends for the study.

However, long-term projections are less reliable than short-term data, where larger uncertainties can affect the scenario results. In addition, all sources of energy are treated in a common way without considering the specific characteristics of the source. This treatment causes some unrealistic behaviours when the specific energy source is considered: e.g. nuclear plants shut down before reaching the planned lifetime.

Nevertheless, the adoption of these general long-term trends to the world scenario study provides reasonable boundary conditions for assessing the shortages of resources and the facilities needs, as extensively described in Chapters 3, 4 and 5.

In order to characterise each region (by the definition of the initial conditions), a world subdivision has been adopted. In particular, IIASA [8] adopts a refined subdivision into 11 groups successively collapsed in three macro-regions (i.e. industrialised countries, reforming economy countries and the developing countries). IPCC adopts the same subdivision but with a different way of collapsing in macro-regions [9]. The IPCC subdivisions as well as the 11 zones considered by IIASA are indicated in Figure 1.

In particular, the following four macro-regions have been adopted as reference in the study:

- IPCC-1 composed of Central and Eastern Europe (EEU) and newly independent states of the former Soviet Union (FSU);
- IPCC-2 composed of North America (NAM), Western Europe (WEU) and Pacific OECD (PAO);
- IPCC-3 composed of Centrally Planned Asia and China (CPA), South Asia (SAS) and Other Pacific Asia (PAS);
- IPCC-4 composed of Latin America and the Caribbean (LAM), Middle East and North Africa (MEA) and Sub-Saharan Africa.

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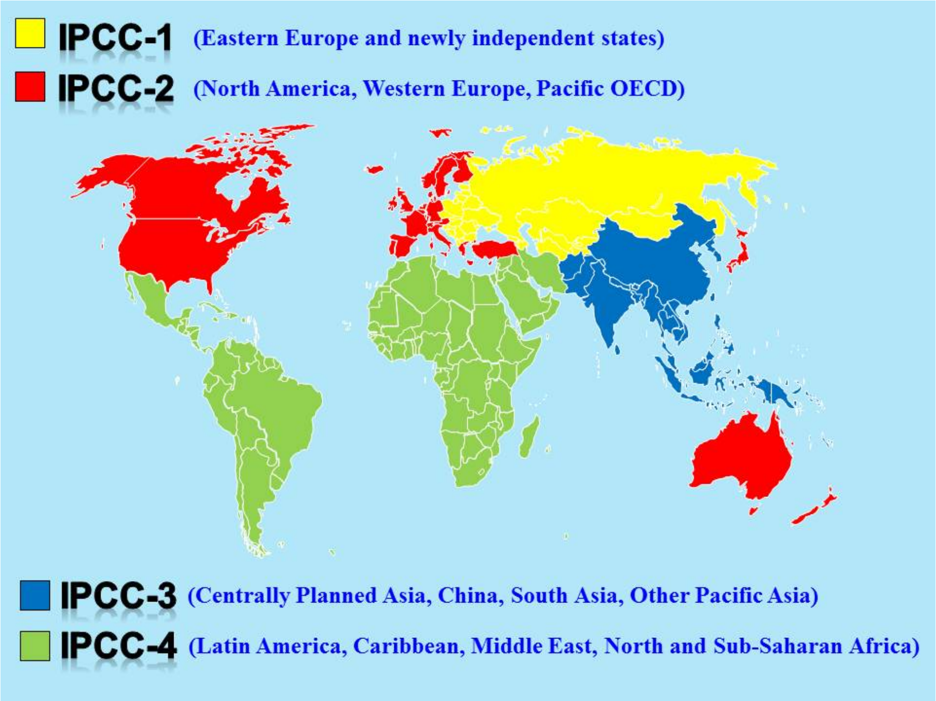
[3] The energy sub-division of the B2-MiniCAM scenario looks questionable for what concerns the nuclear energy demand (see Section 2.2.2.), therefore the subdivision adopted by the *Middle Course* scenario proposed by IIASA has been applied.

Figure 1: The IPCC world subdivision adopted [8] [9]



2.2.2. IPCC emission scenarios and energy projections

The Intergovernmental Panel on Climate Change is one of the international institutions that provide energy projections and environmental evaluations for a long-term time period.

In 2000, the IPCC supplied to the scientific community a series of 40 scenarios, with the aim to investigate, on the basis of a few selected driving forces and approaches, the panorama of the global future development concerning economic, environmental, and social sectors. Each scenario, collected under the name of "Emission Scenarios" and summarised into the *Special Report of Emission Scenarios (SRES)* [9], is one alternative image of how the future might unfold. For each scenario proposed, the relative environment impact in terms of CO_2 emissions (or other GHG emissions) has been assessed.

To carry out this analysis, the IPCC adopts six different models representative of different approaches to assess GHG emissions.[4]

The proposed scenarios are subdivided into four groups (called "families") on the basis of the adopted rationale:

- A1-family collects scenarios oriented towards economic growth and liberal globalisation;
- A2-family collects scenarios oriented towards economic growth but with a greater regional focus;

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[4] The 6 models are: the AIM (National Institute of Environmental Studies, Japan), the ASF (ICF Consulting, United States), the IMAGE (National Institute for Public Health and Environmental Hygiene, United States), MARIA (Science University of Tokyo, Japan), MESSAGE (IIASA) and MiniCAM (Pacific Northwest National Laboratory, United States).

- B1-family represents scenarios environmentally sensitive where global relationships are strongly indicated;
- B2-family contains scenarios environmentally sensitive with highly regional focus.

For this study, the scenario B2-MiniCAM (one of the scenarios proposed for the B2 family), oriented to environment and regional solutions,[5] has been selected. The nuclear energy projections are shown in Figure 2 [9] [14].

In this scenario, nuclear energy plays an important role up until the end of the century providing 20% of electricity needs in 2100. For the period 2100-2200 a slight increase of 0.25% per year has been assumed [14].

The total energy projection proposed (see Figure 2) has a reasonable increase towards the end of the century (ca. 6 times the energy production at 2010), with a higher rate of increase during the second part of the century. In addition, the value assumed for 2010 (starting point of the scenario study) is ca. 2.900 TWhe/year, a value in agreement with the present world nuclear energy production (2.600 TWhe/year as indicated by [11]).

This global trend (in agreement with the LOW case study considered by the INPRO project [5]) has been applied to the world homogeneous study. The results of the analysis are presented in Chapter 4.

For the heterogeneous world study, hypotheses in terms of regional subdivision have been added. In fact, each region follows its own development (based on the starting characteristics of the region, the expected improvement of quality of life, the expected population growth rate and economy) and the choice of the regional energy projections are crucial points for the heterogeneous analysis. In Figure 3, the regional energy subdivision proposed by the B2-MiniCAM scenario is depicted.

By the analysis of the B2-MiniCAM regional subdivision (see Figure 3), some behaviours seem unreasonable. In particular, IPCC-3 and IPCC-4 nuclear projections look too optimistic and the development followed by IPCC-2 and IPCC-1 does not seem to be representative of the present nuclear energy strategy.

In fact, adopting this subdivision, IPCC-3 increases its installed nuclear energy capacity by ~100 times, producing more than ~50% of the world nuclear energy in 2100. It overtakes IPCC-2 before 2020, building ca. 80-100 nuclear reactors in less than 10 years. The same extremely high increase is indicated for IPCC-4 passing from ca. 0 TWhe in 1990 to 6 000 TWhe/year in 2100 (by this trend IPCC-4 overtakes IPCC-2 around 2035).

The relative behaviour of IPCC-3 and IPCC-4 with respect to the IPCC-2 region makes the B2-MiniCAM subdivision quite questionable.

In order to solve this point, other scenarios have been analysed. Within the B2-family, another scenario (namely B2-MESSAGE) has been taken into consideration. This scenario has different starting assumptions on population and GDP growth with respect to the B2-MiniCAM and hence, the comparison of the results is somehow difficult.

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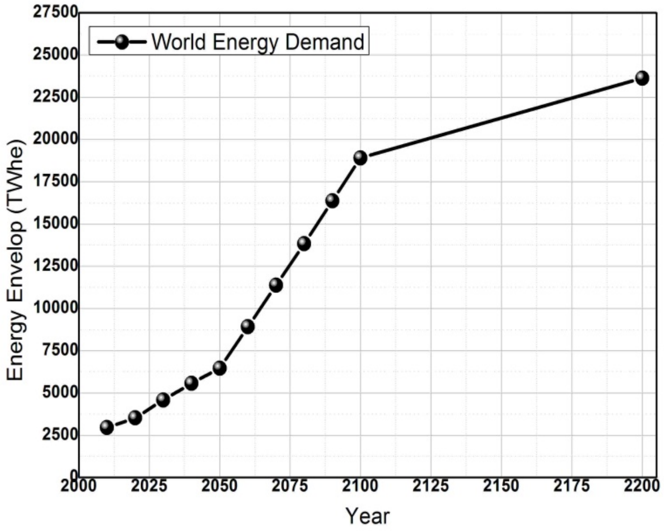
[5] The selected scenario is called B2-MiniCAM from the name of the model adopted.

Figure 2: World nuclear energy projections (TWhe), B2-MiniCAM reference scenario [9] [14]



In the B2-MESSAGE case, the total nuclear capacity in 2100 is double the value proposed by B2-MiniCAM for the same year but the regional subdivision proposed seems more reasonable (see Figure 4).

In this scenario IPCC-2 increases its nuclear capacity more than 3 times before the end of the century passing from ca. 1.700 TWhe in 1990 (value in agreement with NEA data [15]) to 8.140 TWhe. IPCC-1 countries increase ca. 9 times their nuclear capacity. However, the larger increase is due to IPCC-3 and IPCC-4 regions (as the expected growth in population is due in these two regions).

Adopting the B2-MESSAGE subdivision, IPCC-3 overtakes IPCC-2 around 2045, reaching in 2100 a value equal to 2.5 times the level of the IPCC-2 (in 2100). The IPCC-4 follows a very high development as well, overtaking IPCC-2 before the end of the century (around 2075).

These relative behaviours seem more reasonable with respect to the B2-MiniCAM case even though the total nuclear energy projection seems to be too high (in 2100 is ca. 20 times the 1990 value).

This higher energy demand implies completely different results with respect to the B2-MiniCAM scenario, e.g. the stress on uranium resources is expected to happen early, forcing the development of strong breeder systems (with a short doubling time, DT).

Figure 3: B2–MiniCAM: regional subdivision of the nuclear energy projections [9] [13]

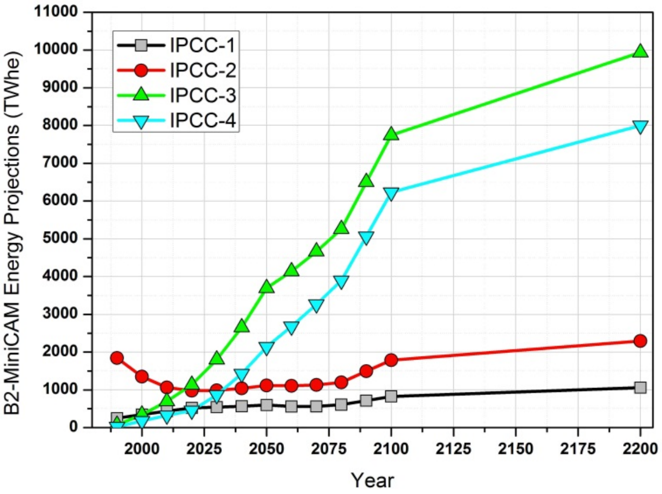
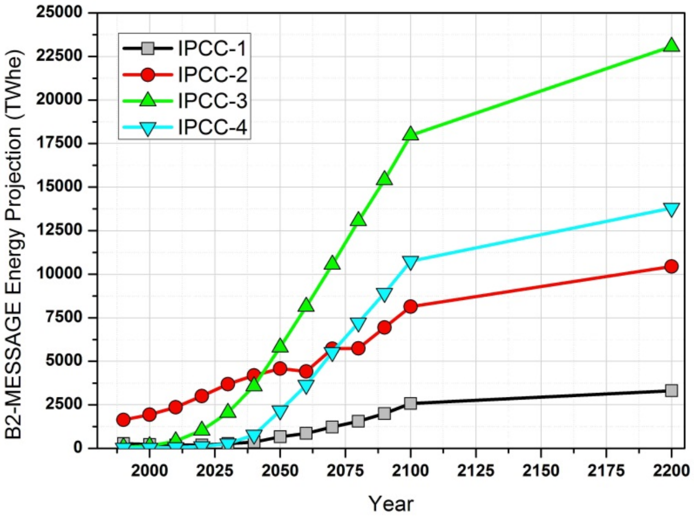


Figure 4: B2–MESSAGE: regional subdivision of the nuclear energy projections [9] [13]



2.2.3. IIASA scenarios and energy projections

Other data sets are provided by the International Institute for Applied Systems Analysis (IIASA) of Vienna. In 1998, it supplied to the scientific community a series of energy-electricity projections (up to 2100) [8] [16].

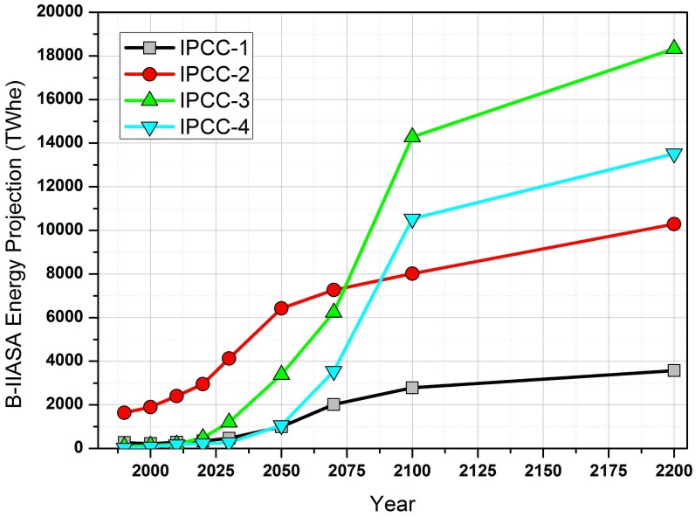
The scenarios proposed by IIASA are classified into 3 groups: 1) “A-scenarios” present a future of impressive technological improvements and consequent high economic growth, 2) “B-scenarios” (or middle-course) describe a future with less ambitious, though perhaps more realistic, technological improvements and consequently more intermediate economic growth and 3) “C-scenarios” present an ecologically-driven future: they include both substantial technological progress and unprecedented international co-operation centered explicitly on environmental protection and international equity [8].

For all the scenarios indicated, the model adopted is the MESSAGE, a model developed internally by IIASA and adopted also by IPCC [8]. Scenario B (middle-course scenario) has been analysed in detail. It is characterised by modest estimates of economic growth and technological development and the demise of trade barriers and expansion of new arrangements facilitating international exchange.

The nuclear energy projection is comparable to the values proposed by the IPCC for the B2-MESSAGE scenario (in 2100, the IIASA total energy demand is about 37 000 TWhe with respect to the 39 500 TWhe considered by IPCC). The regional energy subdivision is shown in Figure 5.

IPCC-3 and IPCC-4 strongly develop nuclear energy, overtaking IPCC-2 towards the end of the century (around 2080 and 2095, respectively). Also IPCC-2 increases its nuclear energy production by about three times with respect to the present value.

Figure 5: B-IIASA: nuclear energy projections by regions [8] [16]



2.2.4. *Energy subdivision adopted for the heterogeneous study*

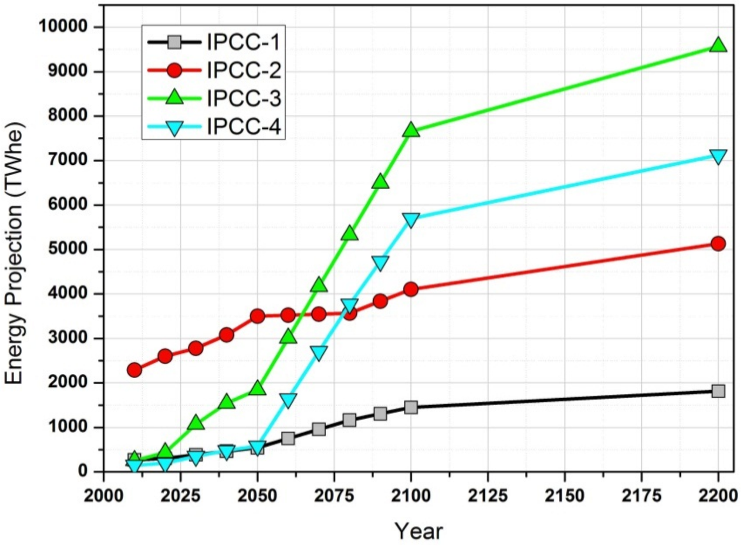
In order to set up as reasonable scenario boundary conditions as possible, the total nuclear envelope proposed by the IPCC (namely B2-MiniCAM scenario) has been adopted for the world study (as indicated in Figure 2) but the regional subdivision proposed by the middle-course "B" IIASA scenario has been rescaled in order to maintain the B2-MiniCAM scenario total envelope.

The values adopted (including the re-scaling) are listed in Table 1 and presented in Figure 6. These data applied in the studies are presented in Chapters 3-5.

Table 1: Nuclear energy projections (TWhe) per region adopted in the world scenario (homogeneous and heterogeneous cases)

	Nuclear energy projections (TWhe)				
	IPCC-1	IPCC-2	IPCC-3	IPCC-4	World
2010	268	2 289	252	145	2 954
2020	301	2 602	431	194	3 528
2030	383	2 780	1 072	348	4 583
2040	463	3 080	1 544	477	5 565
2050	542	3 502	1 846	580	6 472
2060	749	3 524	3 008	1 643	8 926
2070	955	3 547	4 170	2 706	11 380
2080	1 162	3 569	5 332	3 769	13 833
2090	1 307	3 836	6 494	4 733	16 371
2100	1 451	4 104	7 655	5 698	18 908
2200	1 814	5 130	9 569	7 122	23 634

Figure 6: Nuclear energy projections (TWhe) per region, B-IIASA subdivision rescaled to B2-MiniCAM reference scenario total value [11] [16]



2.3. A critical review of current uranium resources estimates

2.3.1. Introduction

In this section the issue of available uranium resources is addressed. The estimates presented here were based mainly on *Uranium 2009: Resources, Production and Demand*

(“Red Book 2009”) [17]. Reasonable hypotheses on uranium availability together with the energy demand projections and technologies adopted represent a crucial point in global scenario studies. For the present study, only uranium resources and associated fuel cycles have been considered. Seawater and thorium resources are not taken into account, although they should be of some interest in the future for some world regions (e.g. India).

2.3.2. Uranium resources estimates

According to [17], the world’s uranium resources have been classified as follows:

- Identified resources: they refer to reasonably assured resources (RAR) + inferred resources and they indicate uranium deposits which were assessed by direct measurement to conduct prefeasibility and, in some cases, feasibility studies. In particular:
  - RAR resources: high confidence in estimates of grade and tonnage are generally compatible with mining decision making standards;
  - inferred resources: are not defined with such a high degree of confidence and generally require further direct measurement prior to making a decision to mine;
- Undiscovered resources: prognosticated + speculative refer to resources that are expected to occur based on geological knowledge of previously discovered deposits. In particular:
  - prognosticated resources: refer to those expected to occur in known uranium provinces that may host uranium deposits;
  - speculative resources: refer to those expected to occur in geological provinces that may host uranium deposits.

Undiscovered resources require significant amounts of exploration before confirmation of their existence and specification of the grades and tonnages present.

Total identified resources as of January 2009 estimates declined slightly in the USD <130/kgU category, but increased in the high-cost category (i.e. <USD 260/kgU), which was re-introduced due to both the overall increase in market prices for uranium since 2003 and increased mining costs.

At the end of 2008, a total of 438 commercial nuclear reactors were connected to grid generating an electrical power capacity of 373 GWe and requiring ca. 59 065 tU/year, as measured by uranium acquisitions. By the year 2035, world nuclear capacity is projected to grow between about 511 and 782 GWe, which represents an increase of 37% and 110% from 2009 capacity, respectively. Accordingly, world annual uranium requirements are projected to rise to between 87 370 and 138 165 tU/year by that date [17]. More refined growth requests (up to the end of the century) can be found in other studies (see next chapters).

It has to be pointed out that while conventional resources are defined as resources from which uranium is recoverable as a primary product, a co-product or an important by-product, unconventional resources are defined as resources from which uranium is recoverable as a minor by-product, such as uranium from phosphate rocks, non-ferrous ores, carbonatite, black schists and lignite. As only few countries have reported updated information, a comprehensive compilation of unconventional uranium resources is impossible at present, so large uncertainties appear in these estimates. Historically, phosphate deposits are the only unconventional resource from which a significant amount of uranium has been recovered. Unconventional uranium resources were reported in “Red Books” beginning in 1965; if uranium prices reach levels in excess of USD 260/kgU, by-product recovery of uranium from unconventional resources is likely to become viable.

"Red Book 2009" reports a total of 16 706 800 tU for conventional resources (RAR, inferred, prognosticated and speculative) [17].

The unconventional resources historically reported in "Red Books" amounts to 7.3-7.6 MtU (dominated by Moroccan phosphorite deposits, which share >85%). This estimate does not include significant deposits in other countries and therefore represents a conservative estimate. Other estimates of uranium resources associated with marine and organic phosphorite deposits point to an existence of almost 9 Mt of uranium in four countries alone: Jordan, Mexico, Morocco and the United States.

The largest estimate ever reported however, which was adopted in our scenario study, is 22 million tU as cited in "Red Book 2005" [18]. This estimate is cited in [19], where resources in phosphate (mostly fertilisers) are reported, for a total of 22 620 234 tU – the largest amount being shared by OECD (and in particular by the United States – see Figure 7).

It is useful to point out that estimated uranium production costs for 50 tU/year as a recovery by-product, including capital and investment, was assessed between 40 and 115 USD/kgU. Moreover, recently the PhosEnergy process was announced by Uranium Equities Limited, according to which uranium should be recovered from phosphate rocks with a capital cost reduction of 50% with respect to past technology with operating costs of USD 44-55/kgU [19] [20].

According to previous hypotheses, a total of 39 327 034 tU is estimated to be available worldwide. Figure 8 shows the subdivision for each category and Figure 9 the geographical distribution according to the IPCC macro-regions considered (IPCC-1, IPCC-2, IPCC-3 and IPCC-4).

Table 1 reports the estimated shares of the uranium distribution in the above mentioned macro-regions according to conventional and unconventional resources estimates reported, respectively, in [17] and [19]: sensible differences are evident; in particular it is relevant to observe that IPCC-3, one of the largest growing economies, owns only 5% of the total reserves.

Seawater was not considered as an economically viable option; nevertheless "Red Book 2009" [17] reports that it has been regarded as a virtually inexhaustible source of uranium since it was estimated that sea contains roughly 4 billion tU. However, because of the very low concentration (3-4 ppb) it was estimated that roughly 350 000 tonnes of water have to be processed in order to obtain 1 kg of uranium. Research in this direction has been carried out in many countries (Germany, Italy, Japan, United Kingdom) [17], but is continuing only in Japan, where a 1 200 tU/year plant is operational with an estimated recovery cost of USD 700/kgU. Research is, however, continuing through pilot trials in order to improve recovery factors and costs.

Nevertheless, issues related to a large scale uranium production from seawater still have to be clarified and therefore this option is not considered in the following.

Concerning thorium, despite that its abundance (9.6 ppm) in the Earth's crust is more than 3 times higher than that of uranium (2.7 ppm), worldwide resources are estimated at about 6.08 million tonnes, including undiscovered resources. The majority of identified resources are in Australia, Brazil, India, the United States and Venezuela. No estimates were provided for non conventional resources. It should be kept in mind that no Th fissile isotopes exist in nature and since the Th-232 isotope (100% of natural Th) is only fertile, innovative technologies have to be developed in order to exploit this resource. However, research in this field is active worldwide (especially in some world regions which have large deposits of this metal and are densely populated, such as India).

Figure 7: Unconventional resources share [17]

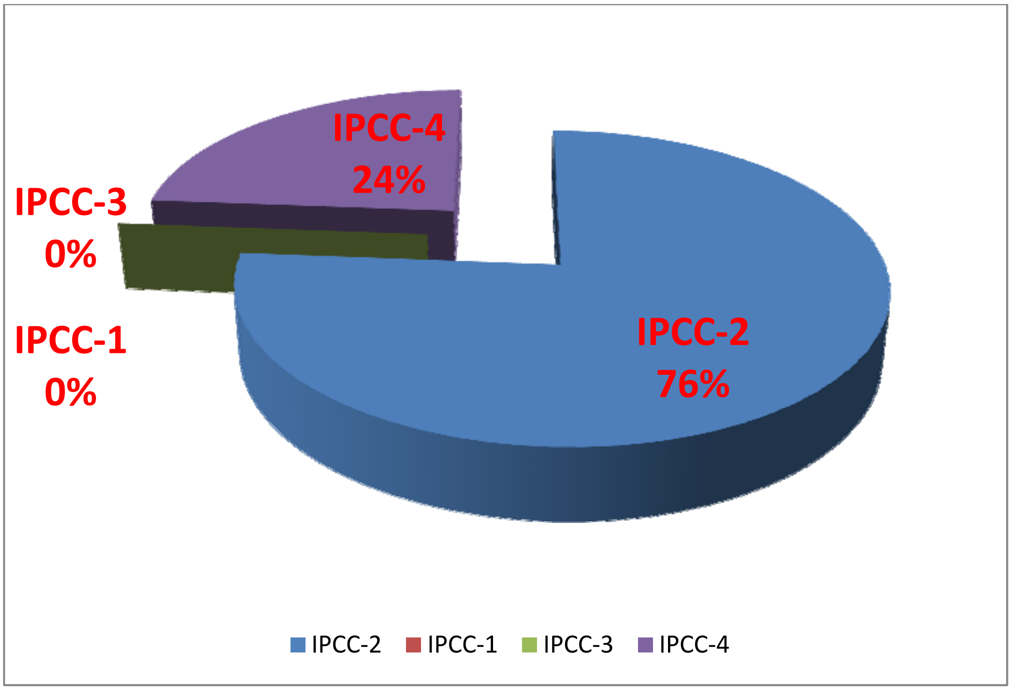


Figure 8: Uranium resources estimates cited in "Red Book 2009" divided per categories and total (in tonnes) [17]

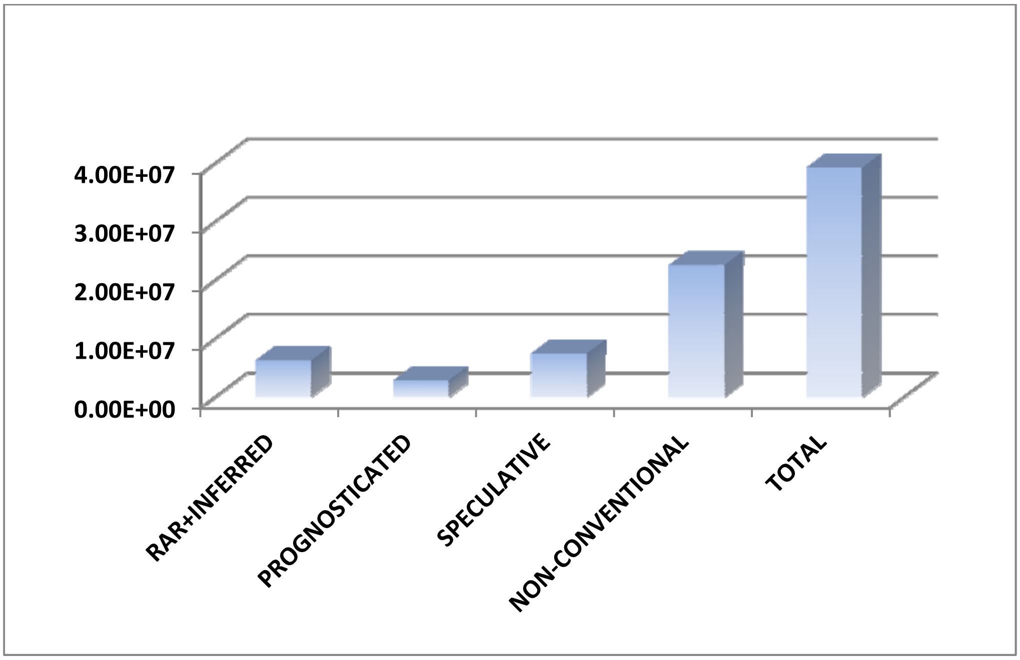


Figure 9: Uranium resources estimates subdivided per macro-region (in tonnes) [17]

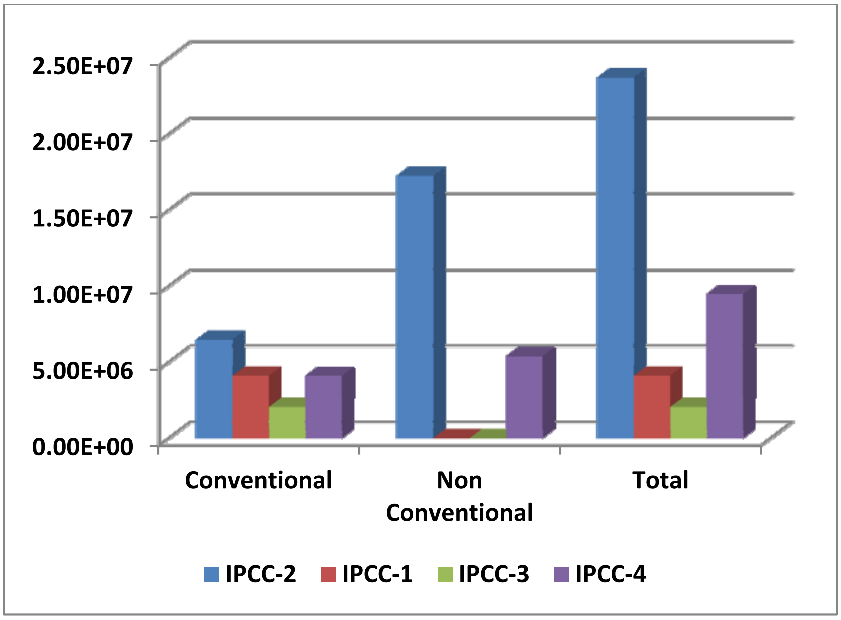


Table 2: Uranium world reserves estimated share

Macro-region	Uranium world reserve estimated share
IPCC-1	11%
IPCC-2	59%
IPCC-3	5%
IPCC-4	25%

Note: conventional [17]+unconventional [19].

2.4. Reactor characteristics adopted in scenario studies

2.4.1. Introduction

A short description of the reactors adopted in the scenario studies is provided here.

COSI6 – ver. 5.2.3 [21] database options were preferred, in particular for PWR and FR with a breeding ratio BR ca. 1.

It has been necessary, however, to develop an original design and library for a strong breeder reactor, required in particular in fast growing economy regions.

2.4.2. Reactor models adopted in the study

The COSI6 software package includes some reactor libraries, both thermal and fast. Nevertheless it was necessary to develop original libraries for breeder systems in order to cope with requirements of fast growing economies. Some details are provided in the following paragraphs.

The thermal reactor model adopted in simulations is part of the COSI6 database: it is a PWR FRAGEMA, with fuel assemblies consisting of an array of 17 x 17 fuel pins, with a power of 1 000 MWe (enrichment and burn-up are case dependent).

Two types of oxide fuelled fast reactors cores were used: a) a reactor with a breeding ratio close to one, already present in the scenario code database and widely adopted by CEA, e.g. [22]; b) a fast breeder reactor, developed by KIT, with a high breeding ratio just sufficient to address the energy growth in fast growing regions.

Fast reactors present in the COSI6 database with a breeding ratio of 1.022 were adopted as “isogenerators”, that is, self-sustaining systems which produce roughly the same amount of fuel that they consume. The main characteristics of these reactors are: sodium coolant, a burn-up of 136 GWd/tHM [22], and a power of 1 450 MWe. The main reactors characteristics are summarised in Table 3.

Table 3: Summary of adopted reactors characteristics

	PWR	ISOGENERATOR
Burn-up (GWd/tHM)	50	136
Cooling time (y)	5	2
U-235 enrichment, Pu content (%)	4.5	21.19
Electrical nominal power (GWe)	1	1.45
Efficiency (%)	34	40
Load factor (%)	85	85
Breeding ratio	-	1.022
Cycle length (efpd)	410	340
Total irradiation time (efpd)	1 640	1 700

2.4.3. Description of the high breeding ratio sodium-cooled fast reactor model

A strong breeder reactor was designed by KIT for the world scenario: a Na-cooled fast breeder system with high breeding ratio (BR ~1.5) and reduced doubling time (~11.7 and 17.8 y, according to two different ex-core lag times). The aim is to model the transition period to optimise the material management, the resource consumption and the fuel cycle infrastructures: reprocessing and fabrication capacities, including possible impact on high-level waste repositories.

The chosen design based on oxide fuel does not necessarily represent an optimised design of the very high breeding ratio fast reactor, in fact dense fuels (like metal ones) could provide a more feasible high breeding FR design. However, for our purposes it was sufficient to introduce a fast reactor which in principle could provide the needed high BR.

The fast breeder model has been assessed by means of the ERANOS code system [23] with the JEF2.2 evaluated nuclear data library [24].

As a starting point the advanced burner reactor (ABR) [25] core was considered. The ABR system consists of 180 fuel sub-assemblies subdivided into two core regions with different enrichments, 114 reflector sub-assemblies, 66 radial shielding sub-assemblies and 15 primary and 4 secondary control assemblies.

The ABR core is loaded with (U-TRU) O_2 fuel and has an internal breeding gain equal to zero. The Pu vector and MA content corresponds to a typical PWR spent fuel composition with discharge burn-up of 50 GWd/tHM after 5 years of cooling, with a MA/Pu ratio ~0.1 and a typical isotopic break down.

Based on the ABR core, a 2D (RZ) ERANOS fast breeder core model has been developed (Figures 10 and 11). Radial and axial blankets composed of UO_2 (99.75 wt.% U^{238}) have been added such that a very high breeding ratio (BR~1.5) has been reached.

The characteristics of the model are shown in Table 4. The core power is 1.400 MWth such that the same power density (MW/tonnes of Pu equivalent) as the Superphénix (SPX) core is obtained.

The doubling times are ~11.7 and ~17.8 years with out of core lag times of 2 and 5 years, respectively. The in pile fuel irradiation time is 1 200 days and the resulting average burn-up is 85.6 GWd/tHM.

Figure 10: Layout of the ERANOS sodium-cooled fast breeder core model

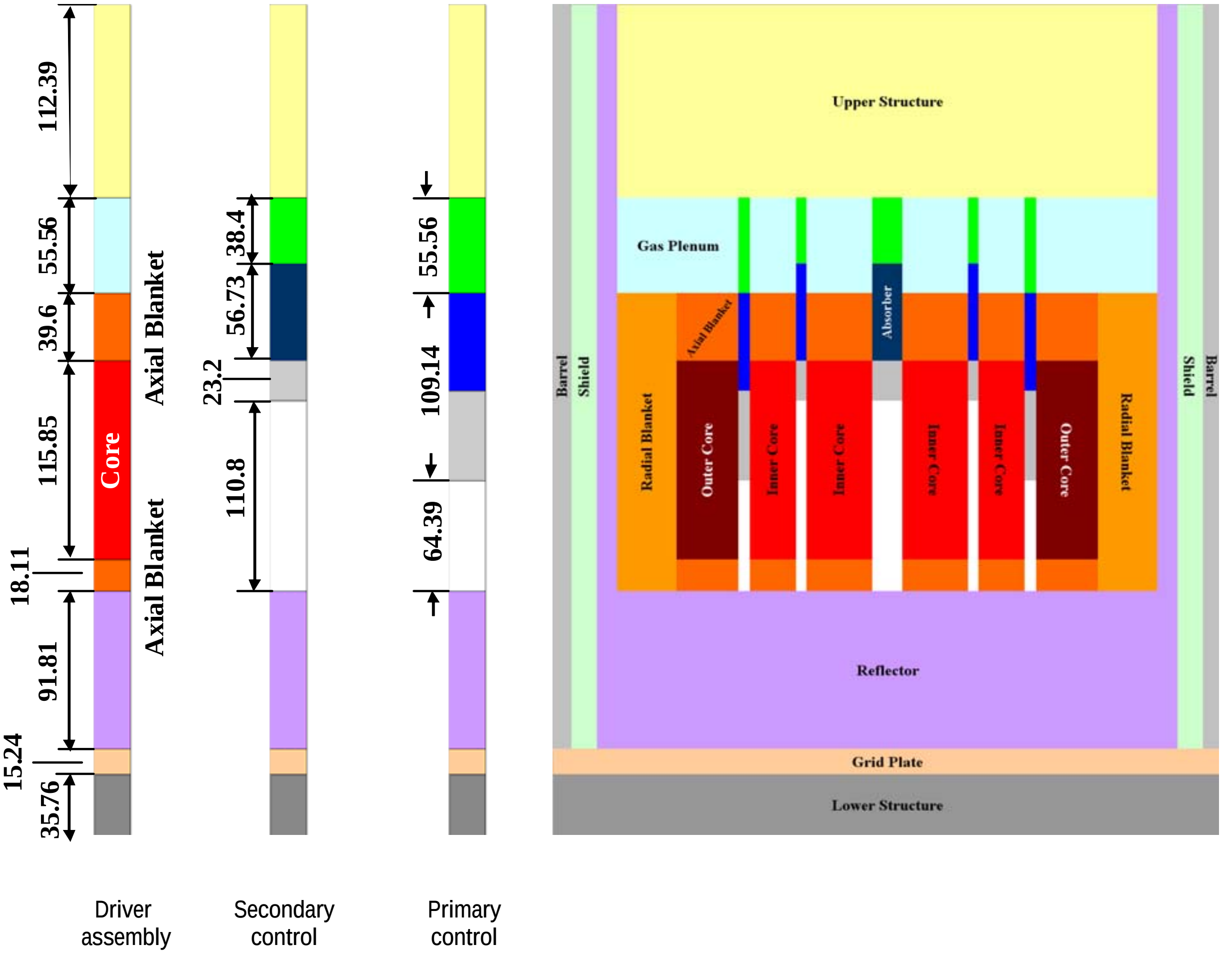
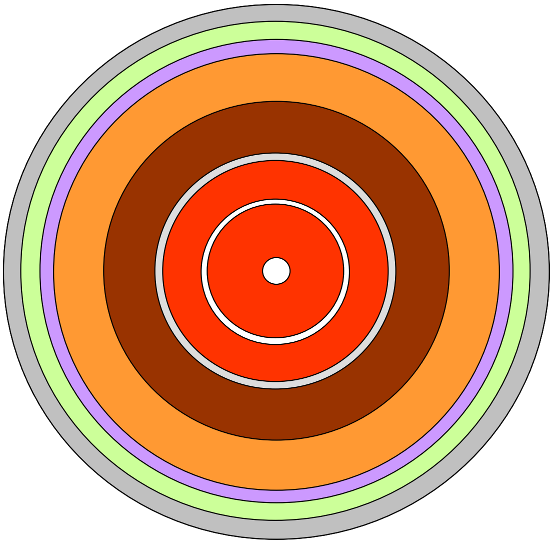


Figure 11: 2D (RZ) layout of the sodium-cooled fast breeder core model at middle height



Region	External radius (cm)
Primary control	8.53
Inner core #1	47.5
Secondary control #1	51.89
Inner core #2	78.65
Secondary control #2	84.0
Outer core	120.34
Radial blanket	155.34
Reflector	166.0
Shield	180.0
Barrel	190.0

Note: The radii of each region are also shown.

Table 4: Characteristics of the ERANOS fast breeder core model: a) axial blanket b) radial blanket

	Breeder
Fuel type	(U-TRU)O_2/UO_2
MA/Pu ratio	0.1
Uranium inventory (t)	7.1/8.7(12[a])/38[b]
TRU inventory (Mt)	8.5/11.0
Pu enrichment (%)	15.8/21.2
Power (GWth)	1.4
Breeding ratio	~1.45
Cycle length (efpd)	400
Total irradiation time (efpd)	1 200

3. World scenario: pressurised water reactors to meet energy demand

3.1. PWRs with limited Pu recycle

The reference case studied considers that the world nuclear energy demand (Figure 2 in Chapter 2) is covered by PWR only (4.2% enrichment and 50 GWd/tHM burn-up). In this scenario Pu is mono-recycled (a reprocessing capacity of 5 000 tonnes/year was assumed) and used for MOX fuels up to 2030 to cover 5% of the total nuclear energy demand. After 2030, only UOX fuel is used. The flow scheme is shown in Figure 12.

Assuming the PWR-based fuel cycle, COSI6 simulations show that conventional resources will be exhausted by the end of the present century, while non-conventional ones will run out at around ~2150 (Figure 13). Stress on resources will appear some decades prior to the predicted exhaustion date if the committed uranium (i.e. natural uranium amount required to feed a power plant during its complete lifetime) issue is addressed (Figure 14). As a consequence of a once-through world fuel cycle, a large amount of spent fuel will accumulate worldwide. By 2150, 4.5 Mt of SF (roughly 400 000 m^3 of heavy metal) will be produced (see Figure 15), posing a significant problem from a repository size (ca. 64 Yucca Mountain size repositories should be required worldwide) and public acceptance point of view, especially in some regions. The spent fuel composition in 2150 corresponds to roughly 65 000 tonnes of TRU, which contain ca. 50 000 tonnes of plutonium and ca. 11 000 tonnes of MA (Figure 16).

With respect to infrastructure, a large uranium demand, also in the case of abundant and low cost natural uranium, will require a significant increase in the number of mines that have to be opened and operated worldwide, potentially posing some significant infrastructural issues. Figure 17 contains an assessment of the number of mines to be opened (as “unit of measure” the extraction capacity of 4 500 tonnes/year has been adopted).

Figure 12: Flow scheme for the PWR modified once-through option

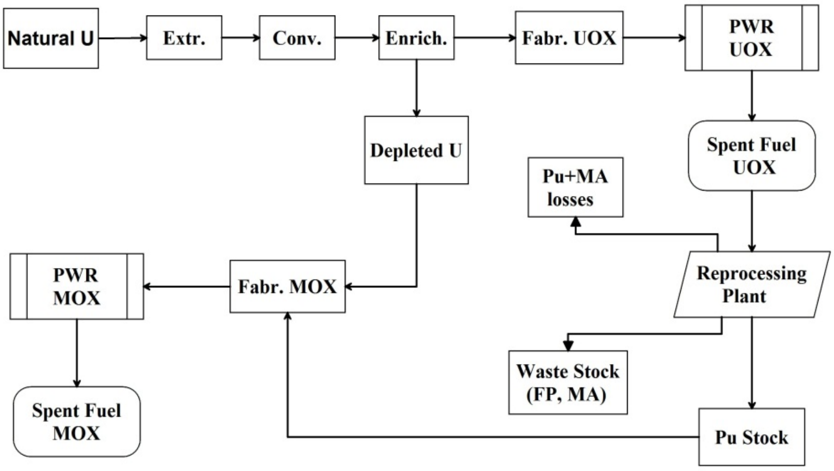


Figure 13: Natural uranium availability vs. time for PWRs once-through case

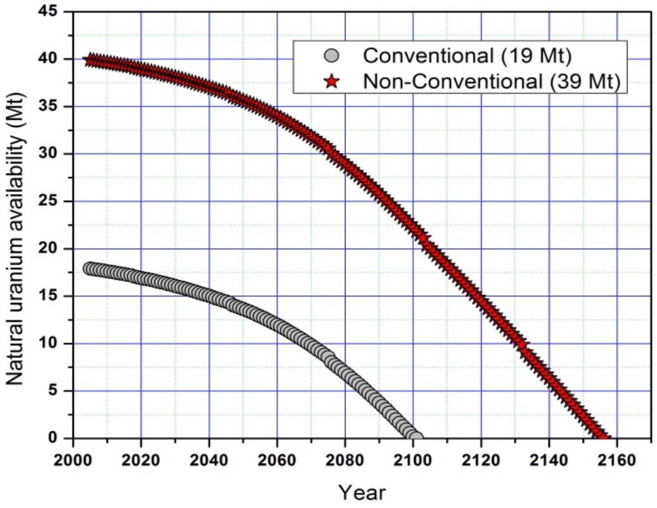


Figure 14: Natural uranium consumed and engaged for PWRs once-through case

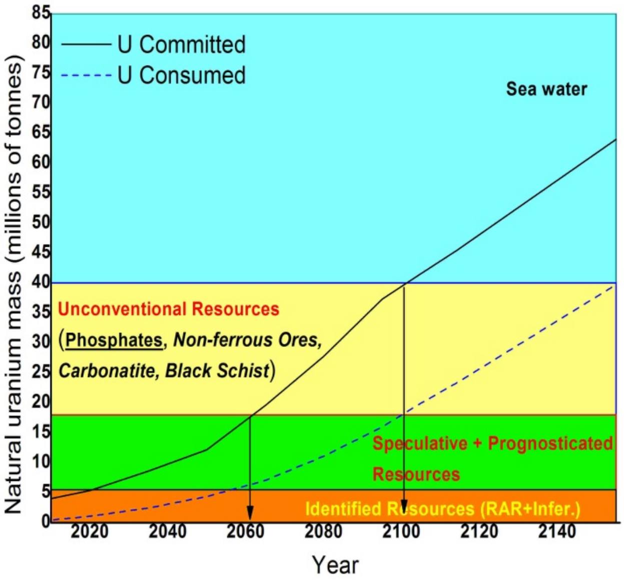


Figure 15: Total spent fuel inventory for PWRs once-through case

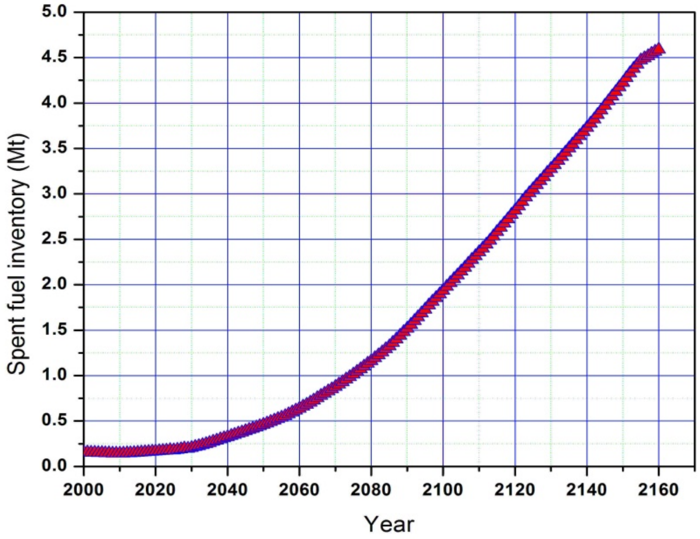


Figure 16: Pu, MA and TRU inventories for PWRs once-through case

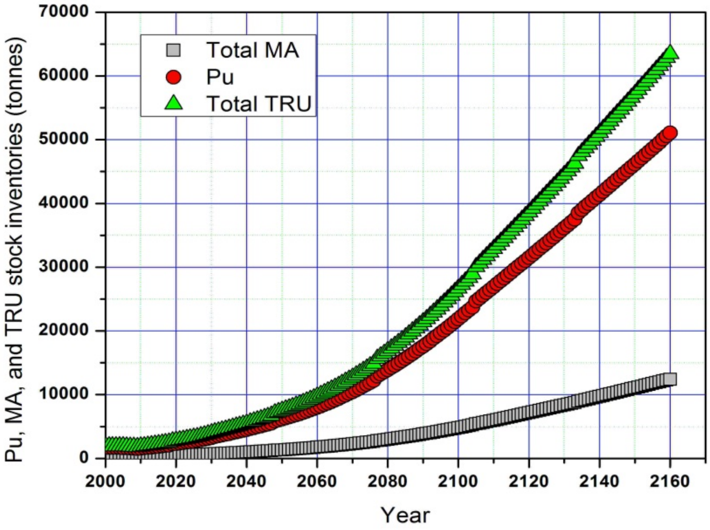
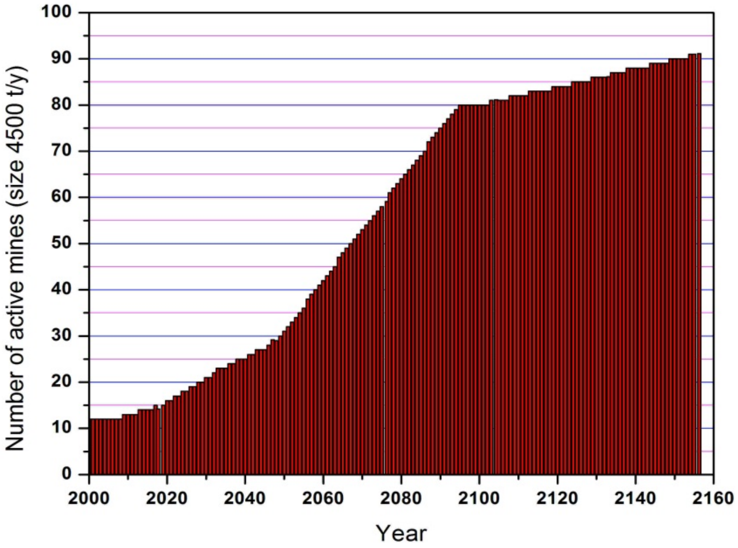


Figure 17: Number of uranium mines (large size: 4 500 tonnes/year) versus time required for PWRs once-through case



3.2. PWRs with extended recovery of fissile materials and variable burn-up

In this section, in order to investigate options to delay the exhaustion of uranium resources, first the option of recovering also uranium from reprocessing is investigated. The flow scheme is shown in Figure 18: a reprocessing plant is added to the once-through fuel cycle and plutonium and recovered uranium (which is still enriched ~1% U^{235}) are sent, respectively, to MOX (which exploits all reprocessed plutonium, producing ca. 5% of the energy demand) and UOX fuel fabrication plants.

Moreover, different burn-up values and different reprocessing capacities have also been considered: 33, 45 and 60 GWd/tHM burn-up and reprocessing capacities of 5 000, 50 000 and 80 000 tonnes/year, respectively.

The burn-up values were chosen in order to cover a range of realistic values (33 GWd/t corresponds to historical PWR burn-up, while it is not widely accepted that burn-ups >60 GWd/t are economically convenient [26]).

The reprocessing capacities adopted correspond a) to the present world value, b) to a steep increase in the present capacity by a factor of 10 worldwide and c) an extreme value related to total fuel mass to be handled.

In Figure 19 the date of the uranium shortage is reported as a function of the assumed reprocessing capacities for each burn-up considered; in this case plutonium is recycled and used for energy production up to 2030. In the 33 GWd/tHM case, uranium reserves will run out before the half-way point of the next century at the present reprocessing capacity. There is only a slight advantage in increasing the reprocessing capacity, as this will delay the exhaustion date by little more than a decade. If higher burn-ups are considered, i.e. present and future values, a slight improvement in resources utilisation is achieved. An increase in reprocessing capacity can still moderately improve the resources utilisation but no improvements are obtained beyond a reprocessing capacity of 50 000 tonnes/year.

Figure 19 shows that a burn-up value of 45 GWd/tHM is preferable from a resource utilisation point of view. This is probably related to the fact that a higher burn-up requires higher fuel enrichment and consequently a large mass of depleted uranium by product is created. In Table 5 the values of enrichment and of enriched to natural uranium ratio are shown (respectively 3, 4 and 6 irradiation cycles were adopted for 33, 45 and 60 GWd/t burn-ups – uranium tailings enrichment being 0.25%, adopting centrifuge enrichment technology): a simple calculation according to these values proves that given a fixed amount of uranium, the maximum energy production is obtained for a burn-up value of 45 GWd/t.

Figure 18: Flow scheme for PWRs cycle with fissile materials recovery by reprocessing

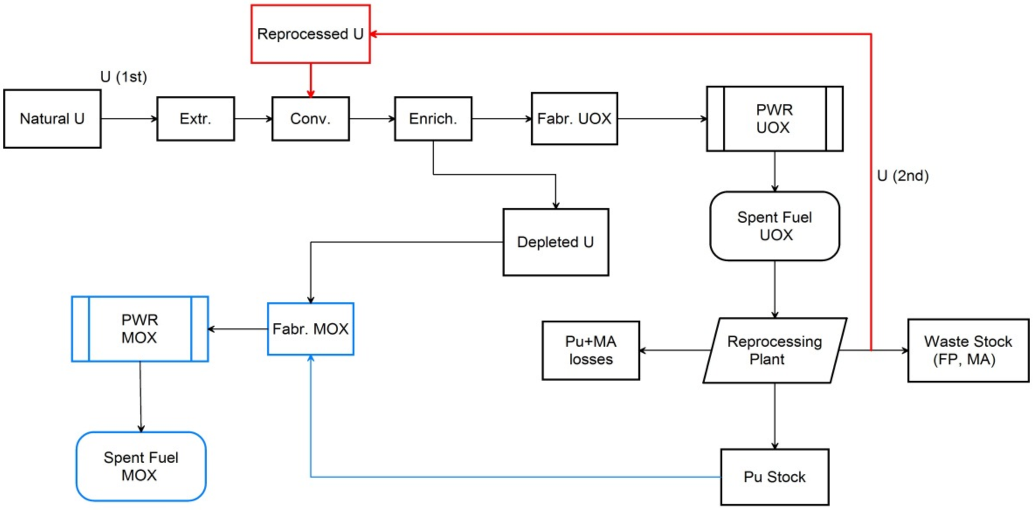


Table 5: Uranium required enrichment and ratio of enriched to natural uranium from enrichment plants for considered burn-ups

Burn-up (GWd/tHM)	Uranium enrichment (%)	Enriched/natural uranium ratio
33	3.2	1:6.3
45	3.8	1:7.55
60	5	1:10.11

The extension of uranium availability is shown in Figure 20. If the present reprocessing values are adopted the uranium shortage will take place practically at the same time with respect to the once-through case, showing that this option is ineffective from a resource exploitation point of view. Slightly more favourable results are obtained if the reprocessing capabilities are increased, but limited to a rather insignificant gain of 10-15 years. This result shows that the considerable effort required for a large increase in construction of reprocessing facilities would not be justified.

In Figure 22 a comparison of different options is shown in order to evaluate the variation of the uranium exhaustion date. The different options are:

- partially closed fuel cycle, burn-up increase versus time and uranium recycling (time schedule as in Table 6), reprocessing capacity: as depicted in Figure 21, no plutonium recycle (I);
- once-through, burn-up increase versus time (time schedule as in Table 6), no uranium and Pu recovery (II). Partially closed cycle, with partial Pu recovery (up to 2030) and complete uranium recovery (up to 2200) 33 GWd/tHM burn-up, reprocessing capacity: 5 000 tonnes/year; this case has already been reported in Figure 19 (III);
- partially closed cycle, with partial Pu recovery (up to 2030) and complete uranium recovery (up to 2200), 45 GWd/tHM burn-up, reprocessing capacity: 5 000 tonnes/year; this case has already been reported in Figure 19 (IV);
- partially closed cycle, with partial Pu recovery (up to 2030) and complete uranium recovery (up to 2200), 60 GWd/tHM burn-up, reprocessing capacity: 5 000 tonnes/year; this case has already been reported in Figure 19 (V);
- closed cycle, burn-up 45 GWd/tHM, uranium and Pu recycling in PWR-MOX reactors up to 2200, increasing reprocessing capacity up to 50 000 tonnes/year (reprocessing capacity increase versus time as in Figure 21), option VI in Figure 22.

The results show that an incremental burn-up does not provide a sensible advantage, while the best option is the adoption of a burn-up of 45 GWd/tHM with a very aggressive reprocessing capacity increase option and utilisation of recovered fissile materials. The results seem to indicate that no option, based only on PWRs, can address the sustainability issue in a satisfactory manner for the long-term. To address the sustainability issue the adoption of fast breeding technologies is to be considered (as will be shown in the next chapter).

Table 6: Burn-up increase vs. time schedule

Time period	Burn-up (GWd/tHM)
2005-2020	33
2020-2060	45
2060-2200	60

Figure 19: Uranium shortage date vs. reprocessing capacity for different burn-up values

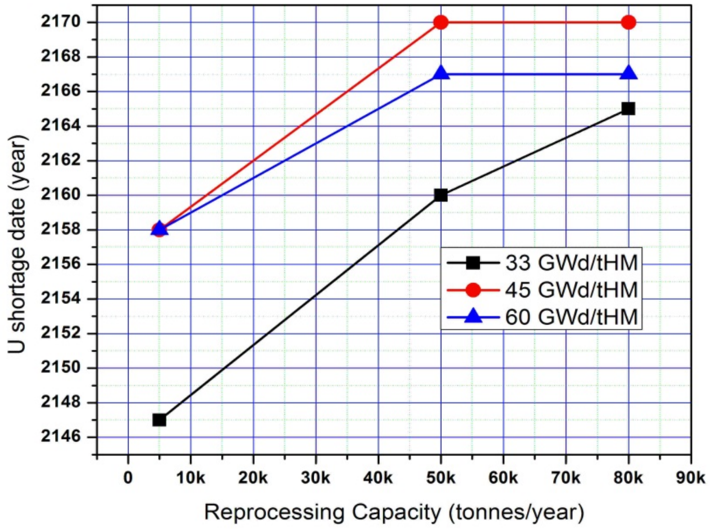


Figure 20: Uranium availability extension vs. reprocessing capacity for different burn-up values

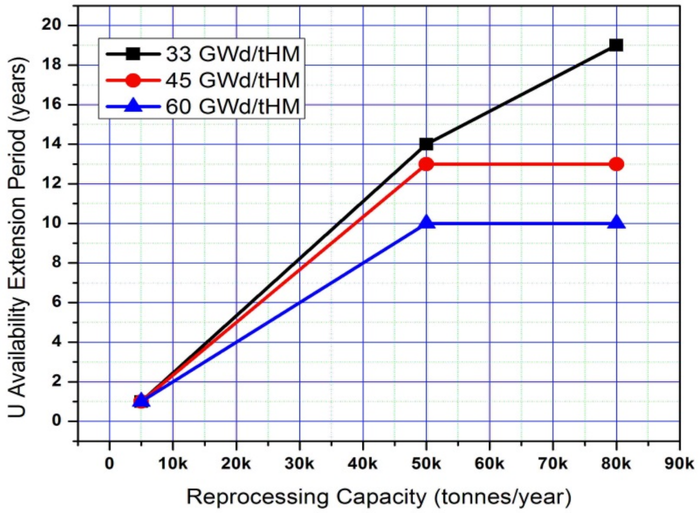


Figure 21: Assumed reprocessing capacity vs. time

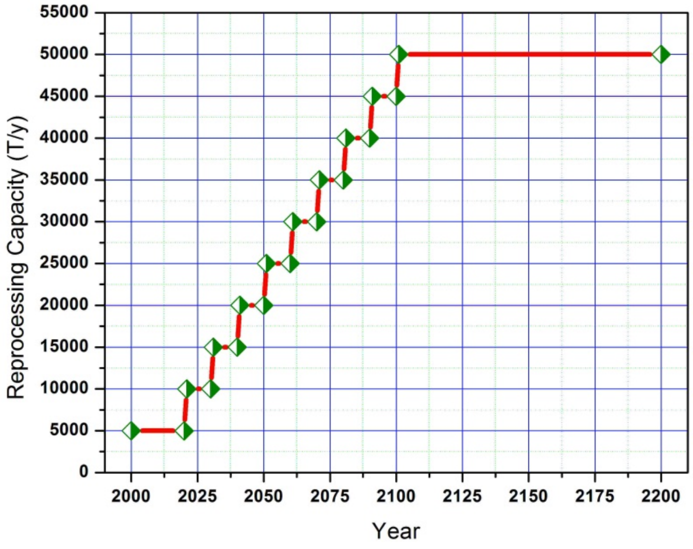
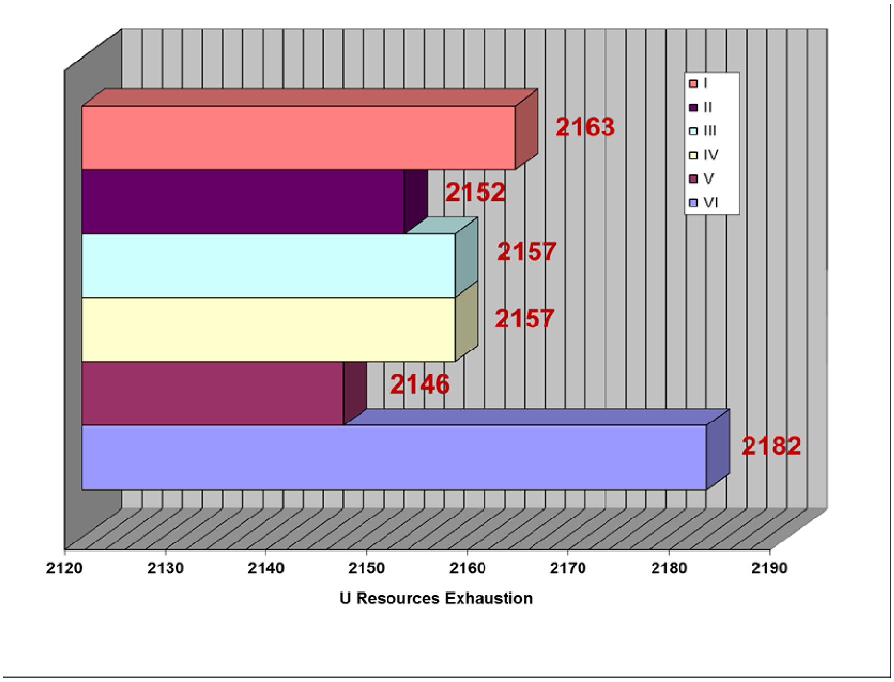


Figure 22: Uranium resources exhaustion date vs. various fuel cycle strategies



Note: Caption explained in the text.

4. Homogeneous world transition scenario with global energy demand growth

4.1. Introduction

Significantly increasing world energy consumption in the present and the next century (see IPCC and IIASA forecasts in Chapter 2) indicates that the need for nuclear energy will continue and its share of the total energy supply should grow worldwide. The objective of the present world scenario is then to assess whether the foreseen demand can be met by specific, optimised nuclear systems.

The nuclear system model developed for the scenario simulation allows monitoring of the flow of key nuclear materials (natural uranium, depleted uranium, plutonium, minor actinides and the total mass of spent fuel) in the front and back ends of nuclear fuel cycle during the evolution of the reactor system and also the determination of the maximum deployable capacity of different reactor classes.

4.2. World transition scenario

It can be foreseen that industrially mature and commercially available thermal reactors will be deployed globally in the next couple of decades. Since these reactors operate on enriched uranium fuel with once-through fuel cycles, they steadily consume natural uranium resources. In Chapter 3, a world scenario model was discussed in which the energy demand adopted was covered by a continuous use of only the PWR fuel cycle. It was shown that if engaged uranium, i.e. uranium mass needed to fabricate fuel for PWR start up cores and for refuelling of PWR during their complete operational time, is taken into account, stress on conventional uranium resources will appear not later than 2060, whereas the unconventional uranium resource limit will be reached at the end of the century.

In order to address potential future uranium resource shortages different transition scenarios exist [7] [27] [28] and [29]. These scenarios enable the evaluation of various strategies envisaged for the future of nuclear energy, from an open, PWR-based fuel cycle to a closed fuel cycle with fast reactors.

For the closed fuel cycle scenario, a dynamic model of the nuclear energy system can be considered in the scenario simulation that consists of a mix of light water reactors and fast breeder reactors, with a progressive replacement of PWRs with FRs, according to resources availability. The light water reactors in this scenario are fuelled with uranium oxide and the fast reactors are loaded with MOX fuel containing depleted uranium (from PWR uranium enrichment facilities) and recovered plutonium. This reactor system has the potential to deliver the required electricity production and improve the efficiency of uranium resource utilisation.

In order to accumulate plutonium needed for FR deployment as soon as possible, no recycling of plutonium in PWR has been considered. In fact, it has been seen in the previous chapter that a limited recycle of Pu in the PWRs does not have a major effect on the resource optimisation. In the closed fuel cycle the PWR spent fuel is reprocessed and both the recovered plutonium and MA are used to fabricate fuel for initial FR cores. The transuranics contained in the discharged fuel of FR are separated and recycled in fast reactors.

The transition from a system dominated by a once-through cycle to a closed cycle based on fast reactors will most likely span over several decades. Scenario studies allow examination of the transition period and help to identify key fuel cycle parameters that strongly influence the transition speed driven by the availability of nuclear material to commission fast reactors.

One purpose of these investigations is to determine the maximum deployable capacity of fast reactors that is consistent with sustainable development and also the fraction of energy produced by the supporting thermal fleet. The main goal of transition scenarios is then to track the mass flow of nuclear material present in a cycle. Apart from this scenario simulations provide information about the size and capacities of infrastructure, including the fabrication and reprocessing facilities needed to manage nuclear fuel supply in order to start up new and operate existing reactors. Note, however, that according to adopted transition scenario specifications no limitations are applied to the enrichment, reprocessing and fabrication facilities, thus their annual capacity is computed in the scenario to satisfy the demand.

4.3. Homogeneous world approach

As a point of departure a simplified homogeneous world approach was chosen. In this approach the world is represented by one single region. Such treatment implies the free flow of fuel resources (fresh and spent fuel) among countries and a free transfer of enriched uranium and fissionable materials separated during SF reprocessing. The purpose of these scenario studies is to illustrate the evolution of the modelled reactor system driven by the global energy demand in the transition phase and beyond.

The main objective is to investigate within a closed cycle the performance of different FR classes and to assess the amount of natural uranium resource saved by tuning scenarios in order to achieve the shortest transition time with the maximum possible share of FR.

The pace of deployment of fast reactors depends initially on the available inventory of recovered plutonium from PWR spent fuel and FR spent fuel legacy inventories. Later on, plutonium recovered from discharged FR spent fuel and discharged blanket sub-assemblies are put back into fast cores. The mass of generated plutonium in FR depends on the breeding ratio (BR), where BR is defined as the rate of fresh plutonium produced from fertile isotopes during the irradiation time of the fissile fuel in the reactor core divided by the rate of plutonium consumed at each pass through the reactor. High breeding ratio implies that more fissile material is produced than destroyed, thus it shortens the transition period length and reduces in turn the mass of consumed uranium. In order to assess the impact of BR on resources two representative FR classes were adopted in the simulation model, with BR~1 and BR~1.5.

In the first case low breeding ratio (BR ~1) sodium-cooled European fast reactor (EFR) of French design [22] (see Chapter 2) was used. The core of the reactor is loaded with MOX fuel containing depleted uranium and plutonium with some fraction of MA. It is an isogenerator (with axial and radial blankets) which may be a preferable option for countries with a prospering nuclear economy and significant plutonium mass accumulated in spent PWR fuel storage. EFRs transmute MA, thus MA inventories present in a cycle can be stabilised at the national or even the regional level if MA are homogeneously recycled in a fissile fuel. Isogenerators are a viable option in national and even regional transition scenarios driven by a constant energy demand or a low nuclear energy growth rate [27] [28]. Their performance in a long-term transition fuel cycle driven by global energy demand with high growth rate – as applied here – has not yet been investigated.

The deployment pace of isogenerators depends in a very sensitive manner on the plutonium mass recovered from light water reactor spent nuclear fuel and thus requires increased fuel reprocessing and fabrication capacities [32]. Moreover, fuel ex-core lag time, as assumed in a cycle, affects the speed of new FR reactor introduction and consequently influences the resource consumption [7]. The purpose of the scenario study is: (1) to illustrate the impact of isogenerator deployment on natural uranium resource and (2) to indicate emerging challenges imposed on FC infrastructure.

In an alternative scenario, instead of isogenerators, advanced high breeding ratio fast reactors (with design characteristics described in Chapter 2) were considered. This option is viable for fast developing world regions with a high energy demand growth rate, but without sufficient stockpiles of reprocessed plutonium. The objective of the analyses was to examine the long-term evolution of the global nuclear reactor system. A sensitivity analysis has been performed to examine fast breeder fuel cycle parameters and their impact on the overall system performance.

All analysed scenarios span over nearly two centuries; the reference period is 2010-2200. Under the hypothesis that both the breeder and the isogenerator fast reactor technologies could be ready for industrial deployment by 2050, this date was chosen in both cases as the beginning of the transition. Fuel ex-core lag time in these simulations includes fuel cooling, reprocessing and fabrication time and was chosen to be 5 years for high-performance breeder, resulting in a composite doubling time (CDT) of 17.8 years. CDT is a measure of the time needed to produce enough plutonium mass for doubling the entire reactor fleet by means of identical reactors.

Sensitivity analyses investigating fuel cycle kinetics imposed by the composite doubling time (CDT) (and BR) have been performed. In order to achieve faster FC kinetics, the composite doubling time was reduced to 11.7 years by imposing a shorter ex-core lag time, which is given by the sum of cooling and reprocessing times for discharged subassemblies of radial and axial fertile blankets and which was assumed to be 2 years. Spent fuel from PWRs was cooled 5 years before reprocessing; PWR fuel fabrication and reprocessing time amount each to 0.5 years. In the time period 2030-2200 no limitations were imposed on reprocessing and fabrication capacities. 0.1% reprocessing losses for TRU were assumed for all fuel types and reprocessing methods. This value is an extrapolation from the current technology to a technology which can be expected to work in the future when advanced fuel cycles could be introduced on a large industrial scale. The actinides which are not recovered and all fission products were assumed to go to the high level waste interim storage.

All analysed FR fuel cycle models implement P&T with multi-recycling of transuranics in a closed cycle. Due to the complexity of the transition scenario implementing advanced fuel cycle models and future innovative reactor designs, a dynamic fuel cycle analysis code, COSI6 developed by CEA-Cadarache [21], has been used for all assessments. Cycle simulation analysis in COSI code is done by tracking the mass flow as a function of time, location and accessibility throughout the complete fuel cycle i.e. for all front-end facilities (the mine, the enrichment and/or the fuel reprocessing and fabrication plants), the reactor, and the back-end installations, considering also the interim SF storage and the geological disposal.

The outcome of the simulation studies in terms of annual electric energy production per installed reactor class is given in Figures 23 and 24. The limited reactor lifetime of 60 years was taken into account in simulations that vary the PWR fleet shutdown schedule. Even though excess plutonium inventory in a cycle is positive, installed PWR capacity decreases slowly as a function of reactor age.

For isogenerators only a slow stepwise deployment schedule is possible due to shortages in the supply of recovered plutonium needed to fuel start-up cores. In periods when FR energy production is kept constant the surplus plutonium necessary to add new units is generated mainly by PWRs. Over time plutonium mass produced in fertile blankets and recovered is added to the stockpile, but even at the end of the next century a thermal reactor share of 23% is still necessary to cover the total energy demand.

The deployment of fast breeders (with higher conversion ratio) leads to higher plutonium excess and enables a faster transition. Fast breeder reactors can fully cover the total energy demand in the following periods:

- 2140-2200 if longer composite doubling time (~18 years) is postulated;
- 2120-2200 for shorter doubling time (~12 years) assumed.

Simulation results indicate that whatever the fast reactor class, PWRs remain a significant part of the reactor system until the end of the present century due to the assumed energy demand, which exhibits a very steep slope in the time period 2050-2100. Other key parameters having considerable implications on the transition speed are: the spent fuel inventory available for reprocessing in a cycle, composite doubling time (dependent on fuel ex-core time) and the fast reactor breeding ratio.

Different FR options lead to different cumulative masses of consumed natural uranium. In Figure 25 significant reductions of consumed uranium mass with respect to the PWR once-through fuel cycle are demonstrated in scenarios which adopt fast breeder reactors. Consumed uranium mass assessed by COSI6 simulations remains below the conventional uranium resource limit. In contrast, deploying isogenerators causes an exhaustion of conventional resources in ~2110 and of unconventional resources in 2200.

In Table 7 uranium resource consumption (Mt) versus deployment time is shown for different reactor classes. The capacity share of fast systems in the fleet (consisting of PWRs and FRs) in 2100 is around 30% (for isogenerators), 58% (for fast breeders with CDT~18), and 71% (for fast breeders with CDT~12), respectively.

The impact of fast reactor deployment on FC infrastructure is shown in Figures 26-31. The required annual fuel fabrication capacities for different fuel types (UOX and FR MOX) are reported in Figures 26-28 and the corresponding reprocessing throughputs are shown in Figures 29-31. According to scenario hypotheses for high-performance breeders a gradual decrease of reprocessing and fabrication capacities vs. time for UOX fuel is observed together with an increase in FRs fuels. The required throughput (capacities) of FR fuel cycle facilities closely follows the imposed energy demand curve. Deployment of both isogenerators and strong breeders will require an increase by at least a factor 7 of current reprocessing capacities for PWR spent fuel in the time period 2025-2040 in order to make the scenario sustainable in terms of plutonium resource availability. For the two breeder options an order of magnitude increase in reprocessing capacity is needed over current capacities by the end of the present century.

Table 7: Natural uranium consumption (Mt) according to reactor type deployed in scenario analyses

Deployment year	Isogenerator	Breeder		PWR
		CDT~18 years	CDT~11 years	
2 100	15	11	10	19
2 150	29	14	11	39
2 200	39	14	11	62

Figure 23: Nuclear energy production of fast reactor fleet

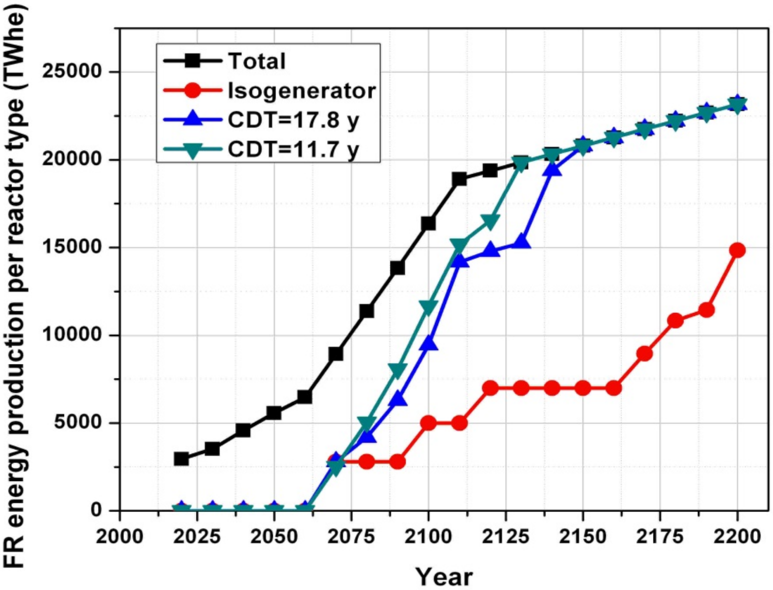


Figure 24: Nuclear energy production of supporting PWR fleet

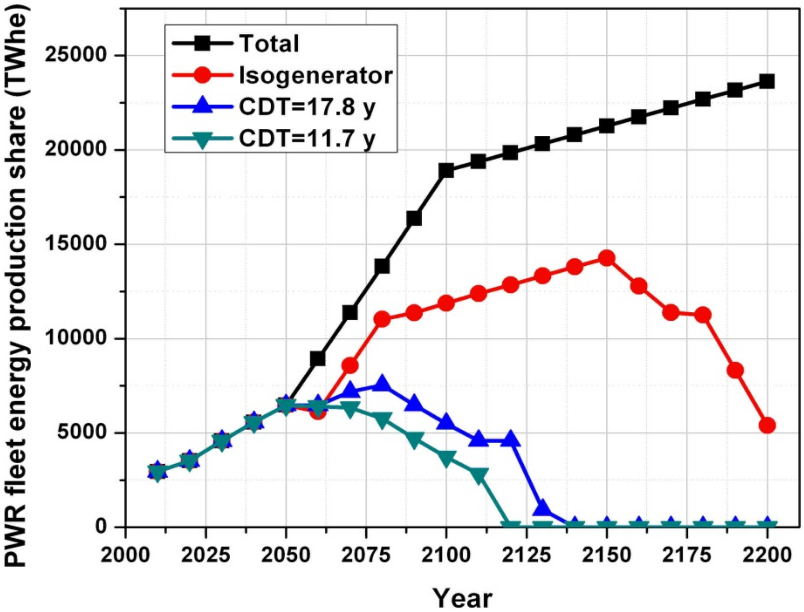


Figure 25: Mass of consumed uranium vs. time for different reactor classes

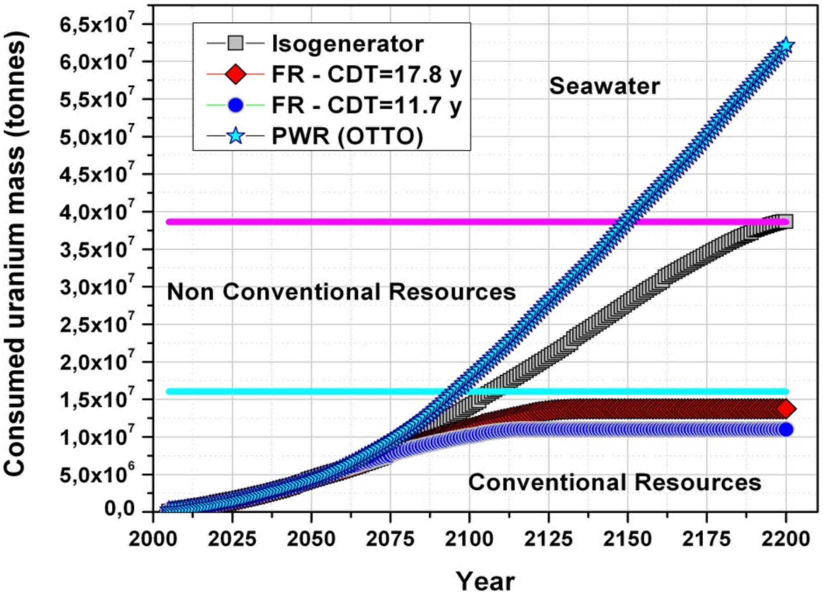


Figure 26: Annual fuel fabrication capacities required for PWRs and isogenerators

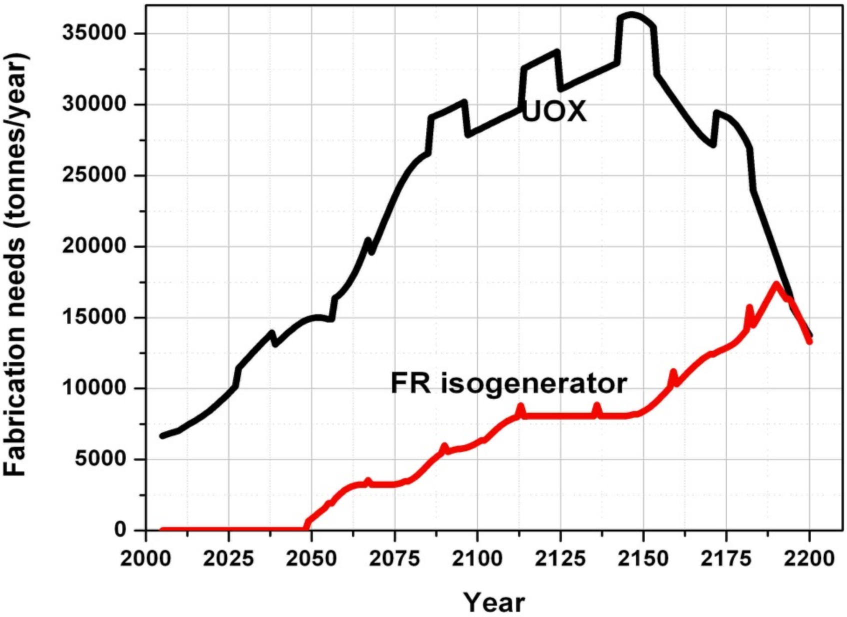


Figure 27: Annual fuel fabrication needs for PWR and fast breeder reactors (CDT= 17.8 years)

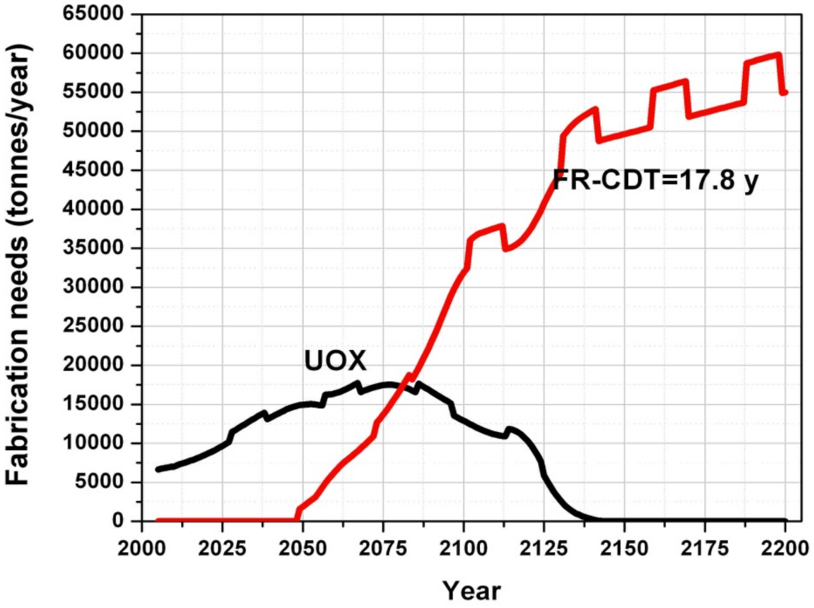


Figure 28: Annual fuel fabrication needs for PWR and fast breeder reactors (CDT= 11.7 years)

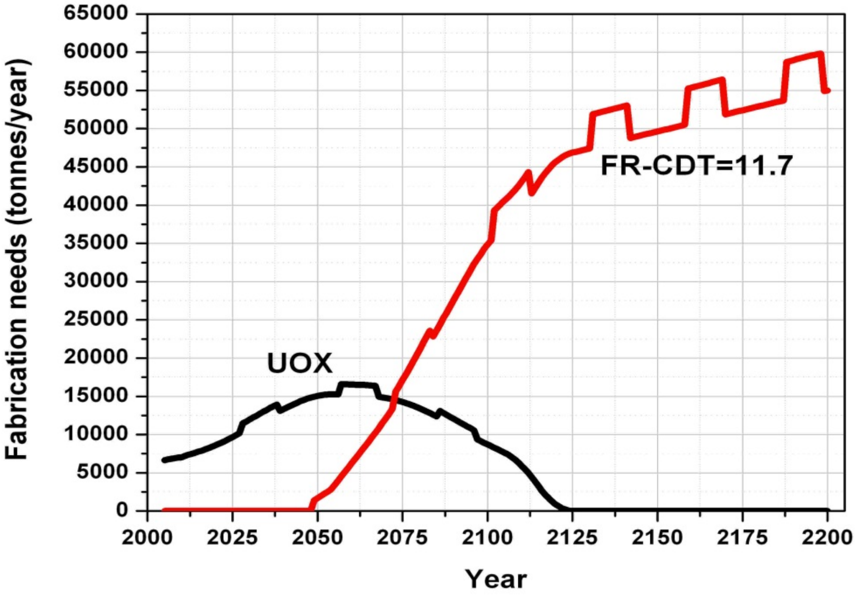


Figure 29: Annual reprocessing needs for spent UOX fuel and spent FR MOX fuel in the case of isogenerator deployment

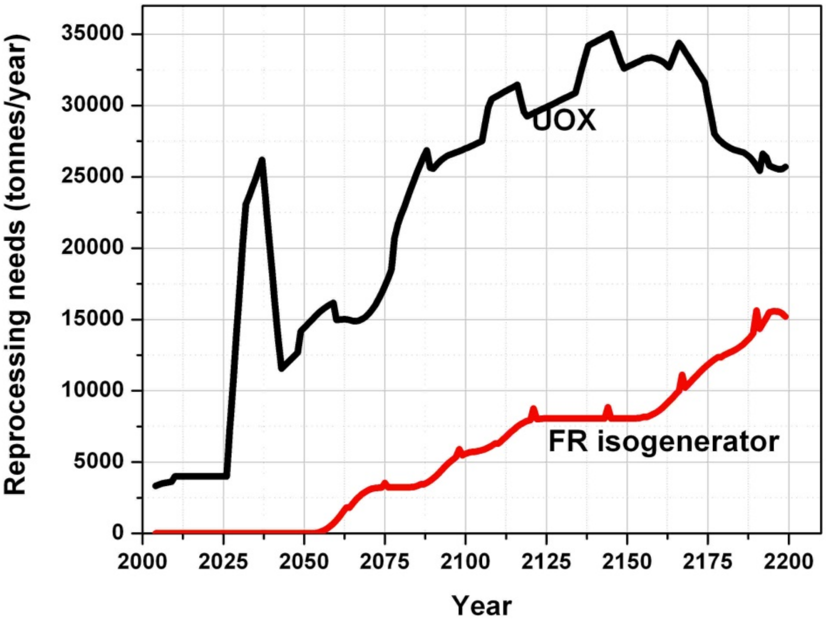


Figure 30: Annual reprocessing needs for spent UOX fuel and spent FR MOX fuel in the case of fast breeder deployment (CDT~17.8 years)

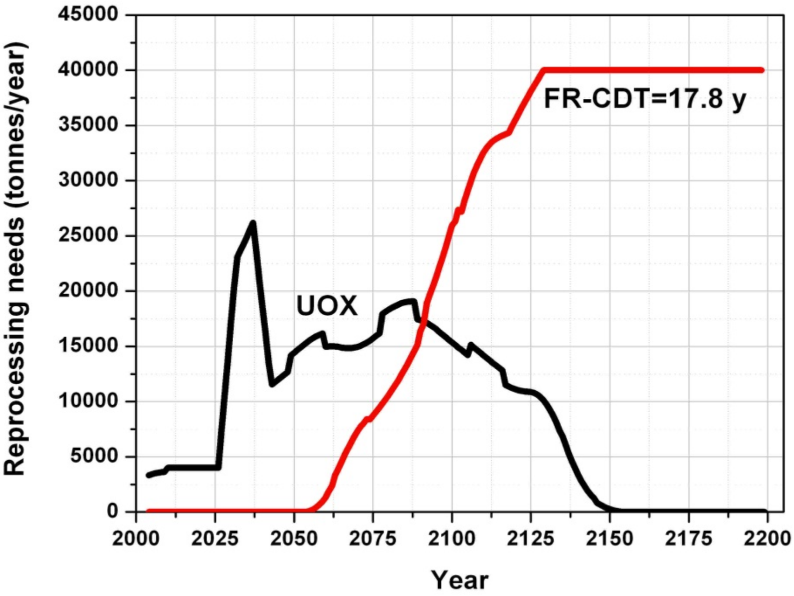
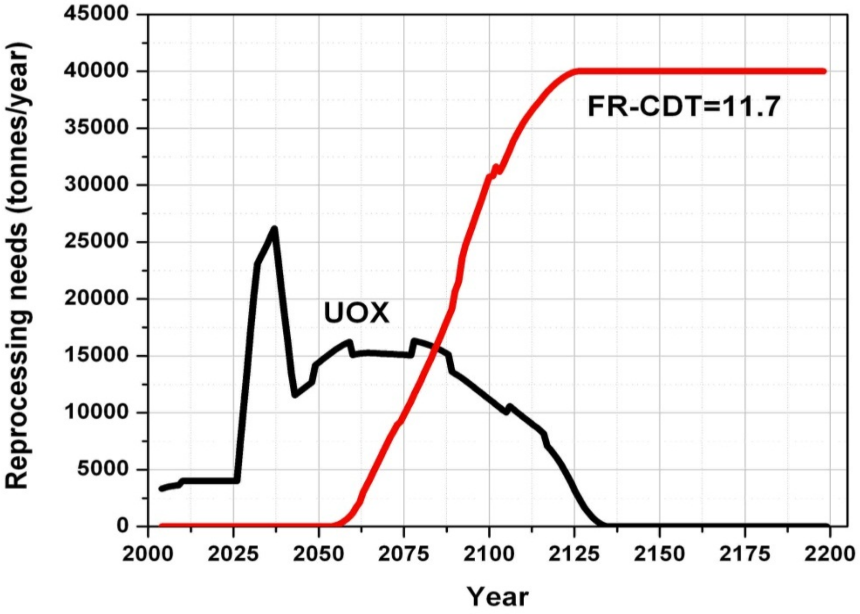


Figure 31: Annual reprocessing needs for spent UOX fuel and spent FR MOX fuel in the case of fast breeder deployment (CDT~11.7 years)



5. World scenario: heterogeneous approach

5.1. Introduction

The world scenarios presented in the previous chapter considered a global nuclear energy demand and a homogeneous approach, i.e. the whole world as a single region. This approach, however, does not take into account sensible differences in energy demands, technology development and rate of deployment in different regions. For this reason an additional study was performed in which the world was split into four macro-regions, namely IPCC-1, IPCC-2, IPCC-3 and IPCC-4, as discussed in Section 2.2 [9] [30].

Some additional hypotheses were required concerning the fast reactor types and date of first deployment:

- IPCC-2 and IPCC-1 deploy fast reactors ("*isogenerators*", i.e. breeding ratio close to one) in 2040;
- IPCC-3 and IPCC-4 deploy high-performance breeder reactors starting from 2060 and 2080, respectively.

The objective of the scenario was to save the maximum amount of natural uranium resources. To this end, a strategy of replacing the thermal reactor fleet with a fast reactor fleet in the shortest time period allowed by Pu availability was adopted.

5.2. Regional (heterogeneous) approach

The energy production envelopes have been described in Chapter 2 and they have been applied to this regional analysis.

It was assumed that there is unrestricted access to uranium between macro-regions, according to demand, while enriched fuel and reprocessed materials cannot circulate due to proliferation concerns.

The spent fuel legacy was subdivided, due to the lack of published data, according to the nuclear energy production share of each region in the reference year 2000, resulting in the following distribution: IPCC-2 ~83 %, IPCC-1 ~10 %, IPCC-3 ~6 %, and IPCC-4 ~1 % [32].

5.2.1. PWR deployment and open fuel cycle

If the "homogeneous" world nuclear energy requirement is met only by PWRs the resource consumption, availability and spent fuel mass accumulation can be assumed as a reference case.

Figure 32 shows the natural uranium availability and consumption versus time. Around 2150, uranium resources, including those from unconventional sources, will be exhausted. According to the same plot, at the end of the century conventional resources (ca. 26 Mt of uranium) will run out, and available uranium deposits will be roughly equal to those consumed, but global energy demand will be much higher than at present. Considering that unconventional resources will have to be exploited, a significant increase in the price of uranium is likely, as is a world market stress on resources, which, in principle, will penalise weaker growing economies. Moreover, if engaged uranium resources are considered, the situation is more complex and stresses on the uranium market have to be expected some decades earlier.

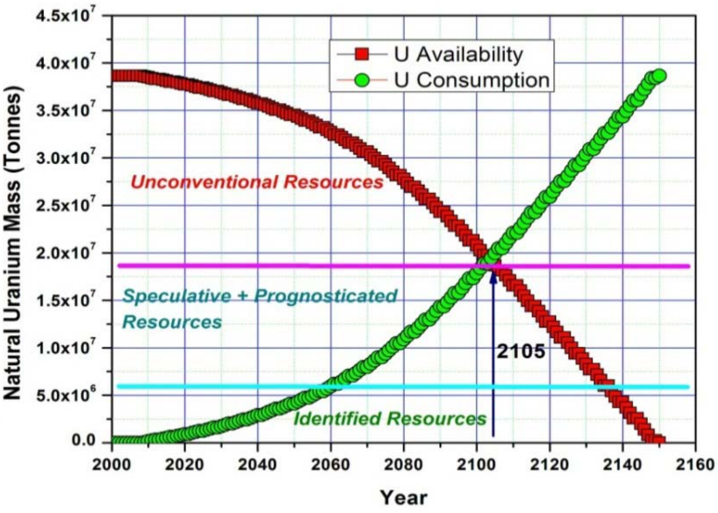
Figure 33 shows the uranium mass requirements for each region as a function of time. The highest demand is in IPCC-3 (ca. 15 million tonnes) due to its high nuclear energy demand, followed by IPCC-2 and IPCC-4 (ca. 10-11 million tonnes). It is relevant to note that IPCC-3 will match the IPCC-2 uranium requirement at the end of the century, after which it will significantly exceed it. Finally, up to the exhaustion of resources IPCC-1, IPCC-2, IPCC-3 and IPCC-4 will have consumed 8%, 29%, 37% and 26%, respectively, of the global available uranium resources. It is worthwhile to mention that the consumption shares mentioned above do not correspond to the actual uranium ore distribution in the world and in particular IPCC-3 should be forced to import heavily, as they own only 5% of the global resources (see Table 2, Section 2.3.2), if thorium or seawater resources are not considered as an option.

With regards to fuel fabrication capacity (Figure 34), IPCC-3 and IPCC-4 require a sharp increase in capacity till the end of present century;[1] after which an increase of about 0.25% per year occurs following the energy demand [14]. The ratios of fuel fabrication requirements in 2100 with respect to the present capacity are:

- IPCC-1_{2100}/IPCC-1_{2010}: 5.5;
- IPCC-2_{2100}/IPCC-$2_{2010:}$ 1.8;
- IPCC-3_{2100}/IPCC-3_{2010}: 26;
- IPCC-4_{2100}/IPCC-4_{2010}: 37.

Spent fuel inventory masses requiring disposal as a function of time up to year 2150 are depicted in Figure 35. IPCC-3 produces the largest amount of SF due to its high nuclear energy production, followed by IPCC-2 and IPCC-4. In Figures 36 and 37 specific ingestion radiotoxicity (expressed in Sv/TWhe) and heat load (expressed in W/TWhe) for the spent fuel are shown (the trends are similar due to the fact that all regions adopt PWRs).

Figure 32: Uranium resource availability vs. time (case: only PWRs)



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[1] Irregular trends, e.g. in Figure 34, are due to discrete nature of the scenario code calculation: different values are expected vs. time according to reactors loading/unloading dates.

Figure 33: Cumulative consumed natural uranium masses subdivided per macro-region (case: only PWRs)

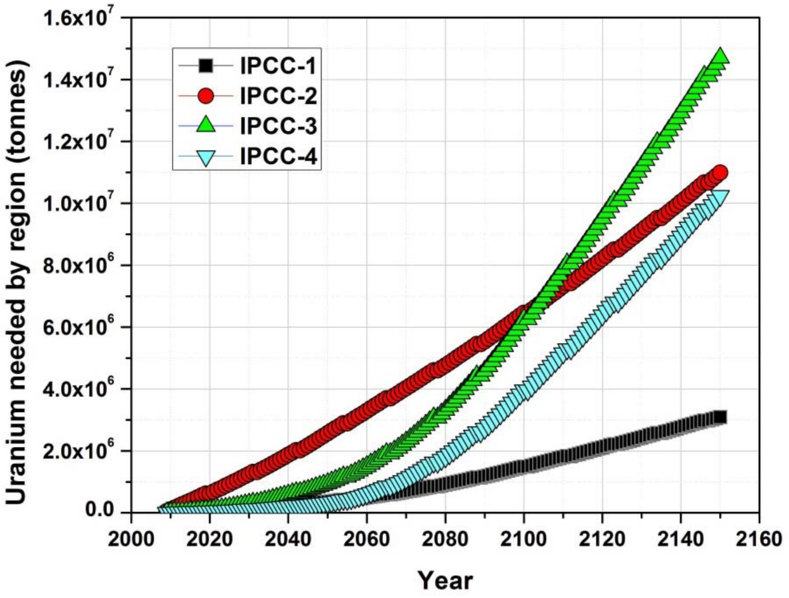


Figure 34: Regional fuel fabrication capacity for macro-regions considered (case: only PWRs)

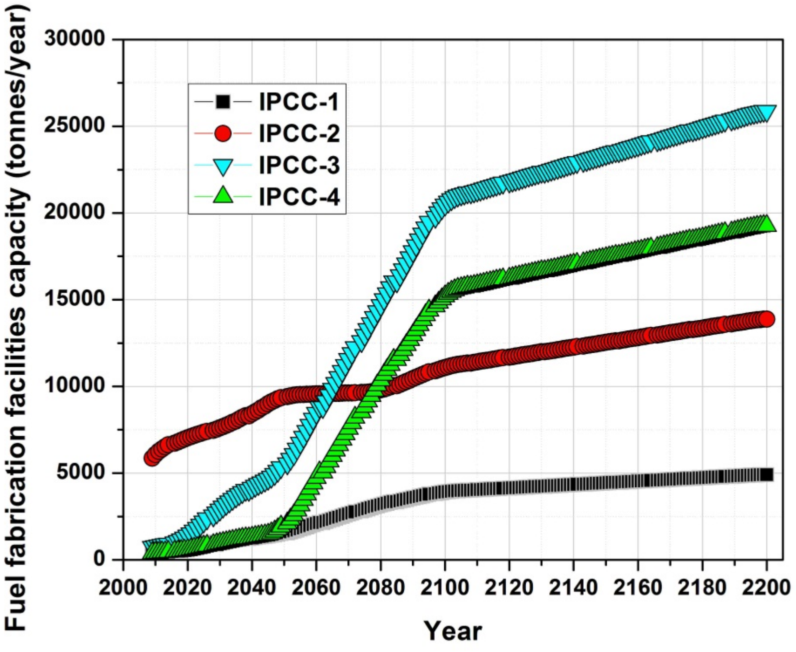


Figure 35: Spent fuel mass inventory per region (case: only PWRs)

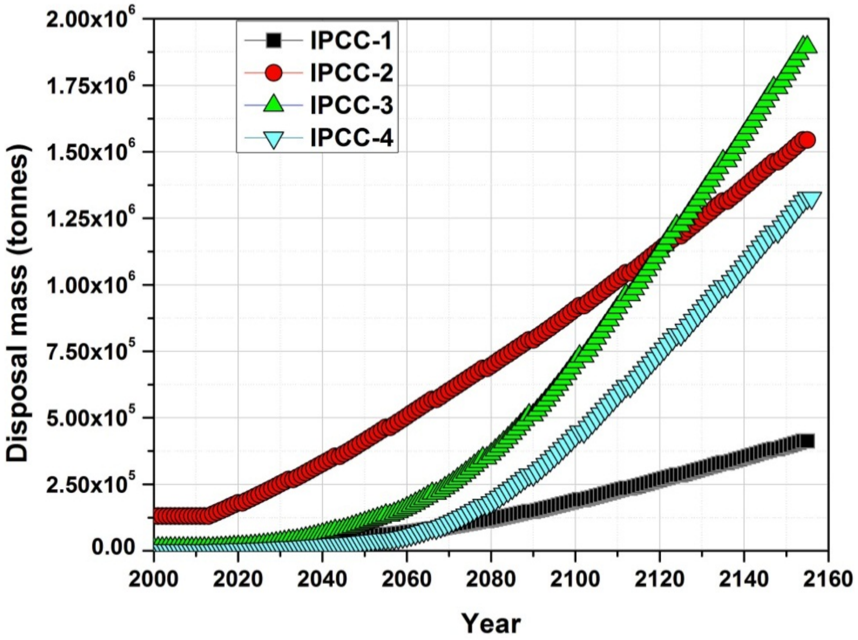


Figure 36: Spent fuel specific ingestion radiotoxicity evolution (case: only PWRs)

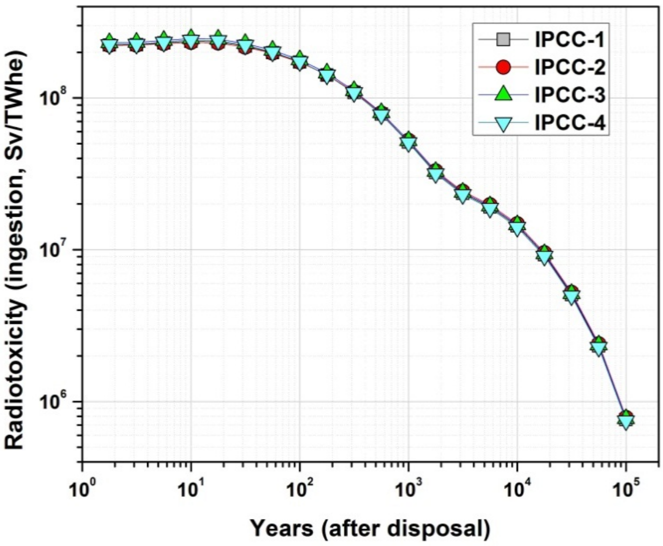
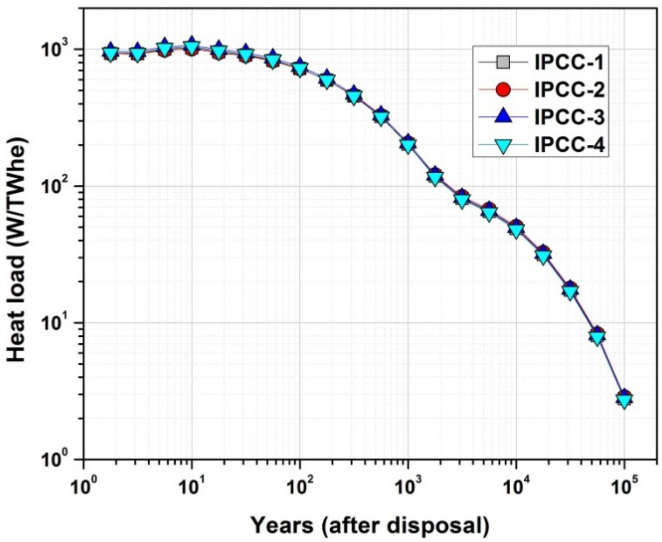


Figure 37: Spent fuel specific heat load evolution (case: only PWRs)



5.2.2. *World transition scenario towards fast systems in a regional approach*

The transition from a regional scenario based only on the once-through PWRs fuel cycle to a fully closed fuel cycle (by the deployment of fast systems in all regions) requires a proper investigation of some fuel cycle parameters, and represents an important challenge if uranium resource utilisation is to be optimised in order to make a rational use of these resources. This should represent an important issue in the future in order to guarantee resource availability and to avoid, or, at least, to minimise, important stresses on uranium markets around the end of the present century. In particular, the ex-core lag time (in our simulations given by the sum of fuel fabrication, cooling and reprocessing times) impacts the composite doubling time and thus the deployment rate of the FR fleet. This in its turn heavily affects the availability of uranium resources, as will be shown. For this reason an ex-core lag time of 2 years was chosen to impose a shorter fast reactor composite doubling time (CDT=11.7 years) in the simulation, in particular for developing regions which present (see Section 2.2) the largest growth rates (i.e. IPCC-3 and IPCC-4).

In Figures 38-41 the total nuclear energy production is plotted for the four macro-regions, and the shares between PWR and FR fleets are detailed. The fleet shares were the outcome of an optimisation process, of which the main objective was to develop fast fleets as soon as possible in order to obtain greatest exploitation of uranium resources. However, these calculations did not take into account the PWR lifetime, which is an unreasonable hypothesis from an economic point of view. For this reason a lifetime of 60 years was considered and the PWR fleet was decommissioned at a correspondingly slower rate, requiring a higher consumption of natural uranium. Table 8 contains the dates for the first and the second cases (i.e. PWRs lifetime not taken into account and the application of a 60-year lifetime) for the complete PWR shutdown (and consequent complete coverage of the energy demand by FRs). Energy demand curves show that the transition from PWRs to FR will last 50 to ~100 years, depending on the region considered.

As discussed previously, in IPCC-3 and IPCC-4, high-performance breeder reactors (i.e. with BR~1.5 and relatively short composite doubling times) were chosen to cope with their assumed high nuclear energy demand and growing rates; FRs introduction was dated, at 2060 and 2080, respectively, in order to make reasonable assumptions. In IPCC-2 and IPCC-1 isogenerators (i.e. BR~1) were used, with their deployment beginning in 2040.

The use of fast reactors with different breeding ratios in the different world macro-regions is mainly driven by the nuclear energy demand growing rates, which are very steep in developing regions (according to the discussed hypotheses). In IPCC-2 and IPCC-1 countries, where a lower increase in energy demand is expected, the deployment of isogenerator fast reactors represents the best choice, as discussed in [27].

However, that choice would be totally unjustified in countries that foresee a much more significant increase in nuclear energy demand. This reveals a significant limitation of all studies related to one specific country or region, in particular if they have already reached a high level of energy production/person, i.e. a satisfactory life standard (as clearly indicated for example by the Human Development Indexes (HDI) in IPCC-2 countries [28]).

Figures 42, 43 and 44 report, respectively, the variation of natural uranium resources with time for three FC options:

- the PWRs "once-through" fuel cycle (in agreement with Figures 32 and 33);
- the PWRs transitioning to FRs in all regions;
- the PWRs transitioning to FR in all regions except IPCC-4 where, in the hypothesis of a much more delayed deployment of FR, the nuclear energy needs are met only by PWRs operating in an open cycle.

In Figure 42 the assumption was made that the thermal fleet is shut down and replaced by fast systems according only to Pu availability, while in Figures 43 and 44 the additional constraints of a reactor lifetime of 40 and 60 years, respectively, were adopted.

Table 8: PWRs shutdown dates for different scenario parameters

Macro-region	PWR shutdown date	
	Reactor lifetime not considered	60-year reactor lifetime considered
IPCC-1	2 140	2 140
IPCC-2	2 090	2 100
IPCC-3	2 110	2 160
IPCC-4	2 130	2 140

For the once-through option, the natural uranium resources will run out at ~2150 and other type of uranium resources such as seawater must eventually be exploited. Otherwise, by adopting fast systems (according to Pu availability) in all regions, the use of unconventional resources (i.e. phosphates rocks, carbonatite, black schist, lignite, etc.) will not be necessary in the case where the reactor lifetime is not strictly respected (Figure 42); in this case, if we refer to homogeneous case with shortest CDT, the mean lifetime of the reactors should be ca. 43 years, with 28% of the reactors shutdown after a 20 years operation time, 14% after 40 years, 33% after 50 years and 25% after 60 years. That is, mine resources will satisfy the global needs, although a significant effort for exploitation of new uranium deposits will be required. In the cases where economic issues prevail and a lifetime of 40 or 60 years is assumed, the adoption of unconventional resources appears unavoidable (Figures 43 and 44). Finally, if only IPCC-4 adopt thermal reactor systems and all other regions transition to fast systems, unconventional resources will have to be exploited around 2110-2120 (according to the hypothesis assumed).

It is interesting to observe that an assumed PWR lifetime of 40 or 60 years does not present a significant impact on uranium resources; the regions are forced to adopt unconventional resources to meet the energy requirements in the next century in both cases. This fact requires explanation, considering that a greatly reduced reactor lifetime should enable a too rapid FR introduction in the cycle, which should prove impossible due to a lack of fissile material; this will force shutdown of the PWR fleet at a slower rate than allowed by the fixed lifetime parameter.

Figures 42, 43 and 44 demonstrate the importance of the adoption of fast reactor technologies; it is widely accepted that the sustainable nuclear energy production option is strictly related to some particular aspects, one of which is that resources will remain available in the long-term. The present analysis shows that even though uranium price currently represents only a minor share of the cost of producing nuclear energy, a development strategy which does not take into account natural resource availability will prevent the adoption of this energy option by future generations.

Delving more into the details, Figure 45 shows the uranium cumulative masses needed if the macro-regions adopt fast systems (FC option 2 in Figure 44). IPCC-3 and IPCC-4 will require very large amounts of uranium; these values are higher than those required by IPCC-2 (especially in case of IPCC-3, by a factor of ca. 2). This is due to the hypothesis of a very aggressive policy of introduction of fast breeder reactor technologies with high breeding gain, short cooling times and early deployment, but keeping a fixed PWR lifetime.

The increase of both fuel fabrication and of reprocessing capacities revealed in this scenario study is one of the most significant results of the present analysis. A large increase in capacity of these facilities will be required in fast growing regions (IPCC-3 and IPCC-4). It should be noted moreover that in the second half of the present century, when fast systems should start to replace the traditional thermal systems, the adoption of new technologies and technical solutions will be required in existing plants. For example, with respect to the present IPCC-2 PWRs UOX required fabrication capacity (~9 000 tonnes/year), the COSI6 simulation indicates that IPCC-3 and IPCC-4 will require a UOX fabrication capacity of ~10 000 tonnes by ~2067 and ~2077, respectively, while in the IPCC-2 countries that capacity will reach ~10 000 tonnes by ~2050. As a result of the FR implementation strategy envisaged in the scenarios, the UOX fabrication capacity requirement will decrease after a few decades and a sharp increase of the FR fuel fabrication is then expected: ~4 000 tonnes in the OECD countries by ~2090; ~18 000 tonnes in IPCC-3 by ~2140 and ~14 000 tonnes by ~2130 in the IPCC-4 group of countries.

When compared with the existing world annual reprocessing capacity (mostly in the OECD countries) i.e. ~3 800 tonnes/year, a value ~6 times higher is expected in IPCC-3 and a value ~4 times higher in IPCC-4 by ~2130, while an increase by a factor ~2-3 is expected by ~2050 in the OECD countries. In practice, this would mean that the IPCC-4 and IPCC-3 reprocessing capacities should be increased by about 1 130 tonnes/year every 10 years (the equivalent to a La Hague size plant every 15 years). Moreover, it should be noted that the accelerated decommissioning of the IPCC-2 thermal fleet presented in Figure 39 will require a peak reprocessing capacity in ~2050, which is a factor of 4.5 greater than the present capacity, followed by a reduction to ~5 000 tonnes/year. It should be argued that this approach is not technically reasonable from an infrastructural point of view. A possible solution to this issue is the adoption of enriched uranium (but this option will not save uranium and may lead to further complications regarding the infrastructure requirements of enrichment plants). Alternatively, a slower rate of FR introduction could be adopted, driven by the infrastructure availability (which appears the most reasonable solution).

These numbers should be taken as a warning message about the potential infrastructure growth issues that are likely to occur, particularly in IPCC-3 and IPCC-4. Even if these difficulties suggest a more realistic deployment pace, some of the challenges facing the different world regions are clearly indicated by the present scenario study.

In Figures 46 and 47 the evolution of the specific ingestion radiotoxicity (Sv/TWhe) and for the heat load (W/TWhe) in the spent fuel is shown for each region (FC option: FRs in all regions). These calculations were evaluated using a simplified procedure and consider only the heavy nuclides. As expected, the specific values in various regions are very similar.

Finally, in Figures 48-51 the mass evolution of MA (Np+Am+Cm) for the PWR once-through scenario (FC option 1) and for the scenario with PWR transitioning to fast systems in all regions (FC option 2) is compared. The bell shape trend in the case of IPCC-2 is a result of the assumed nuclear energy demand (roughly constant between 2050 and 2080, see Figure 39) and the contemporary introduction of FRs for energy production. It was found that the transition to FRs will enable reduction of the mass of the MA produced from by a factor of 1.5 (in IPCC-1) to 10 (in IPCC-2); however, a proper optimisation of the breeding blankets management should improve these figures (by choosing a proper date when radial blankets are removed and running the cores as isogenerators when a suitable amount of Pu is available).

Figure 38: Nuclear energy production share in IPCC-1 (PWRs and isogenerators – 60-year reactor lifetime considered)

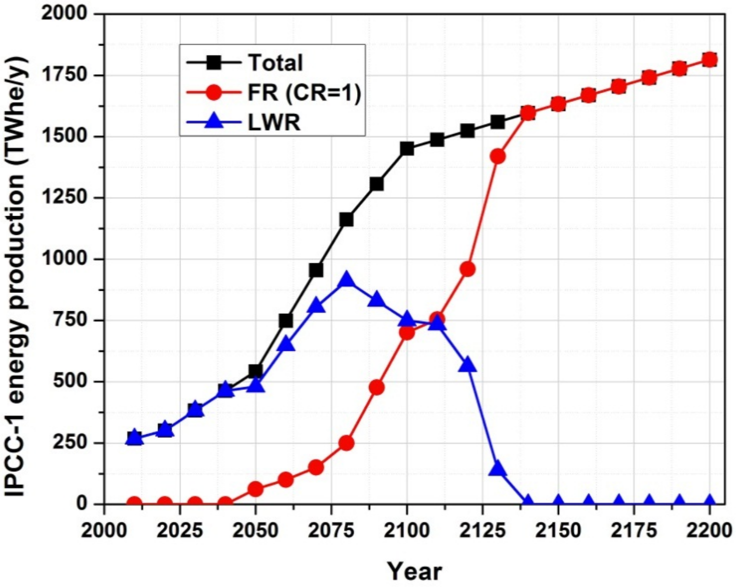


Figure 39: Nuclear energy production share in IPCC-2
(PWRs and isogenerators – 60-year reactor lifetime considered)

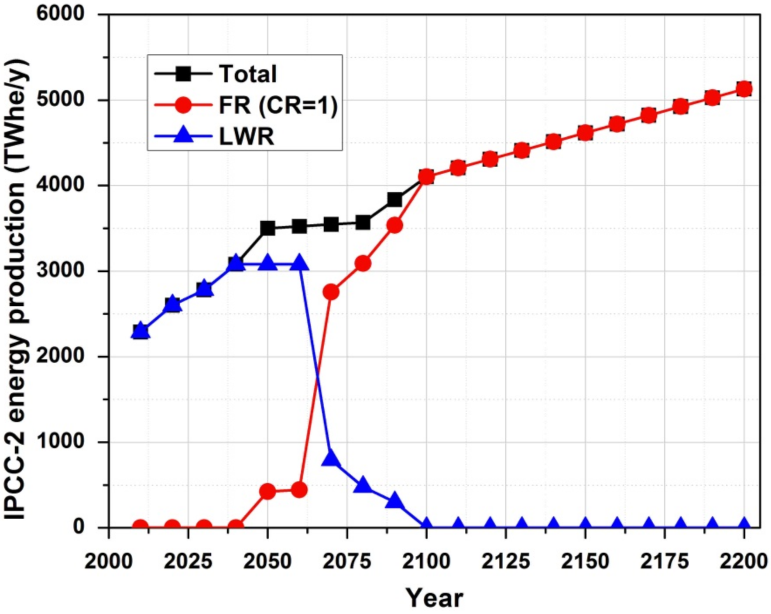


Figure 40: Nuclear energy production share in IPCC-3
(PWRs and breeders – 60-year reactor lifetime considered)

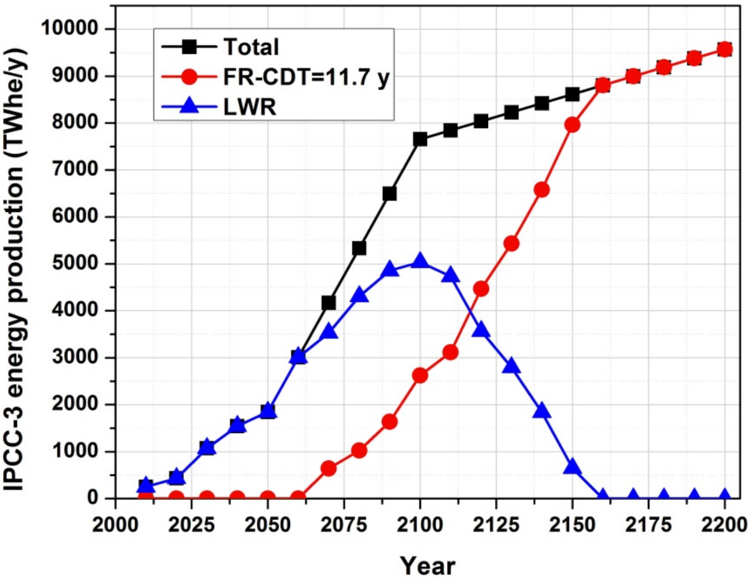


Figure 41: Nuclear energy production share in IPCC-4 (PWRs and breeders – 60-year reactor lifetime considered)

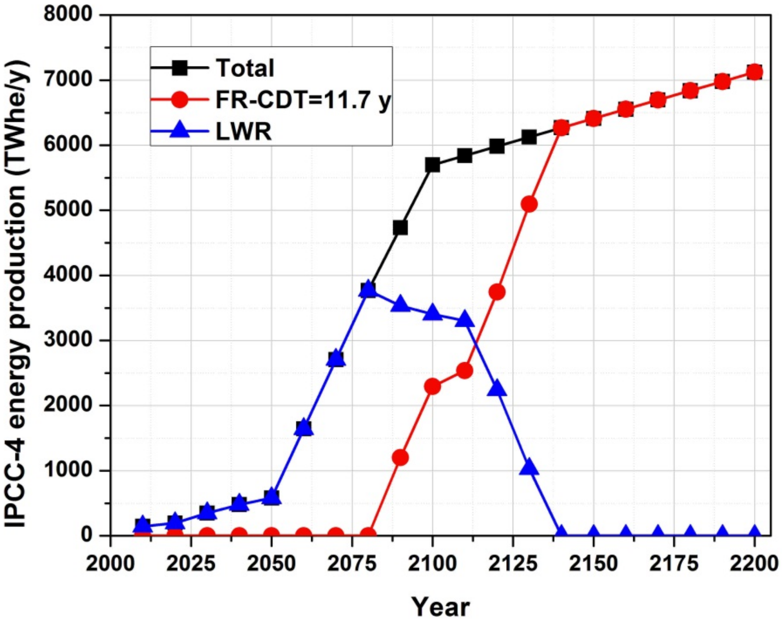
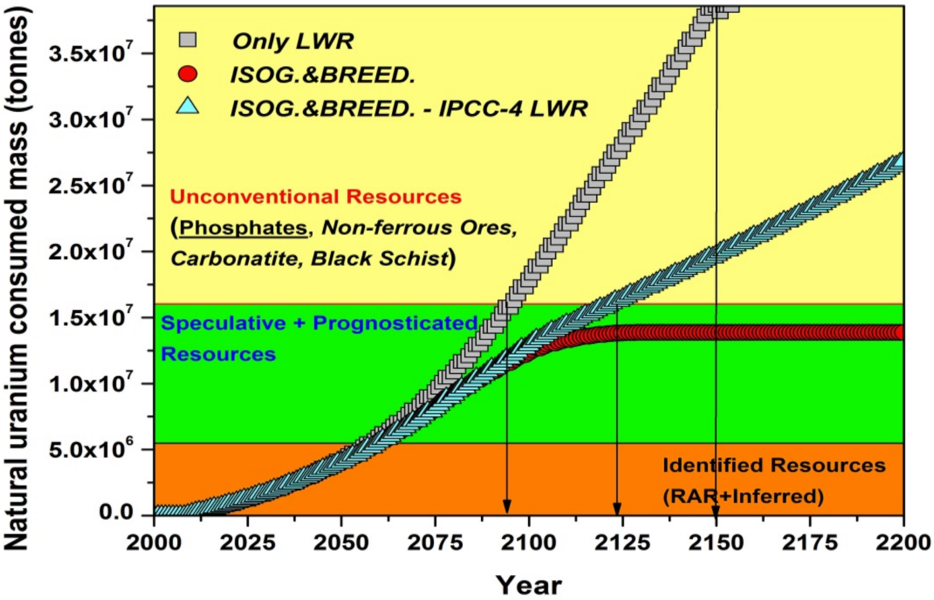


Figure 42: Total natural uranium reserves for three different deployment scenarios

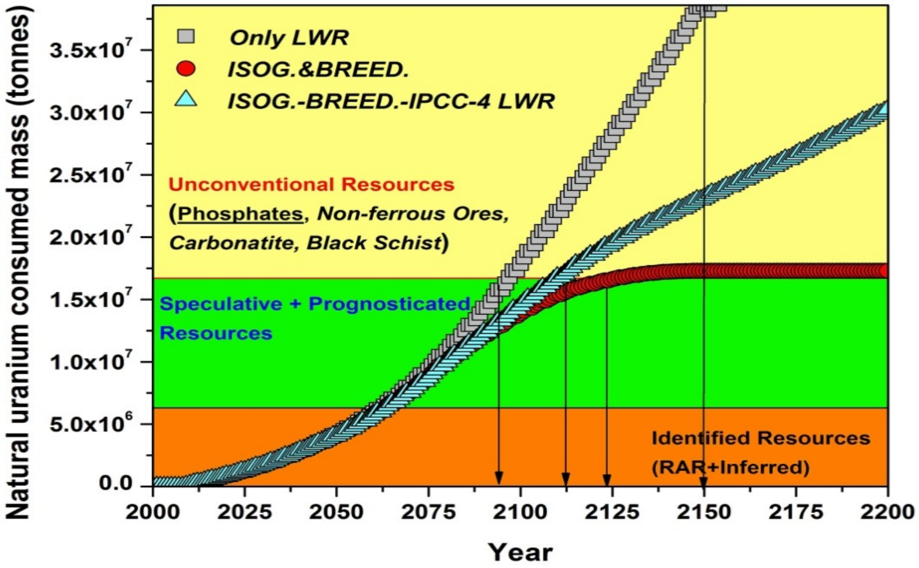
(no PWRs lifetime considered)



Note: (■) FC option 1: only PWRs with open cycle; (●) FC option 2:IPCC-3 and IPCC-4 (breeders) + IPCC-2 and IPCC-1 (isogenerators) (▲) FC option 3:IPCC-3 (breeders) + IPCC-2 + IPCC-1 (isogenerator) + IPCC-4 (only PWRs).

Figure 43: Total natural uranium reserves for three different deployment scenarios

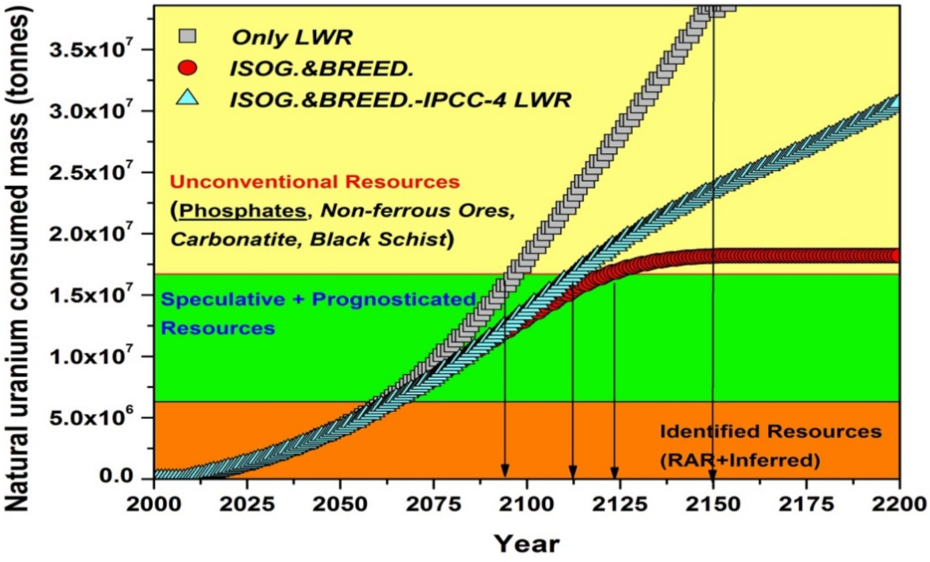
(PWRs lifetime 40 years assumed)



Note: (■) FC option 1: only PWRs with open cycle; (●) FC option 2:IPCC-3 and IPCC-4 (breeders) + IPCC-2 and IPCC-1 (isogenerators) (▲) FC option 3:IPCC-3 (breeders) + IPCC-2 + IPCC-1 (isogenerator) + IPCC-4 (only PWRs).

Figure 44: Total natural uranium reserves for three different deployment scenarios

(PWRs lifetime 60 years assumed)



Note: (■) FC option 1: only PWRs with open cycle; (●) FC option 2:IPCC-3 and IPCC-4 (breeders) + IPCC-2 and IPCC-1 (isogenerators) (▲) FC option 3:IPCC-3 (breeders) + IPCC-2 + IPCC-1 (isogenerator) + IPCC-4 (only PWRs).

Figure 45: Cumulative masses of consumed natural uranium (case: FRs in all regions)

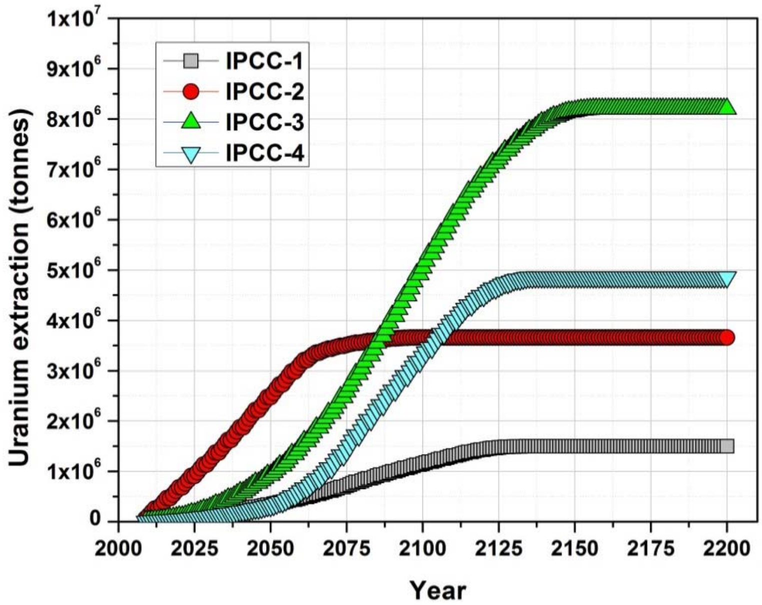


Figure 46: Spent fuel specific ingestion radiotoxicity evolution (case: FRs in all regions)

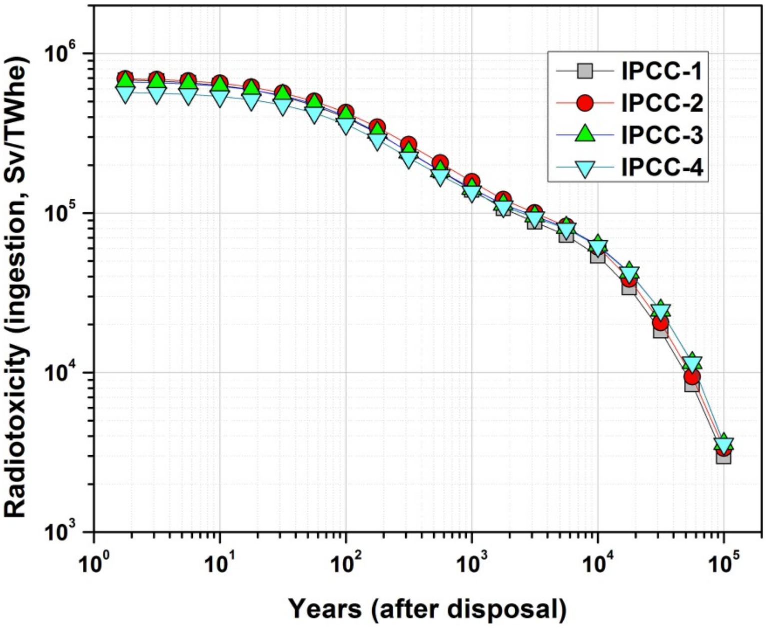


Figure 47: Spent fuel specific heat load evolution (case: FRs in all regions)

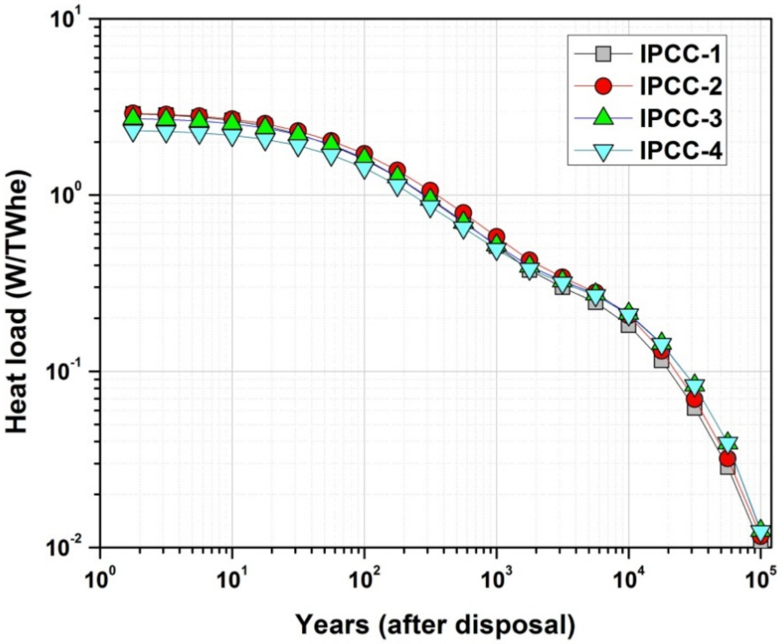


Figure 48: Comparison of the minor actinides (Np+Am+Cm) inventory between the FC option 1 (only PWRs) and the FC option 2 (FRs installed as soon as possible according to Pu availability and 60-year reactor lifetime) in the IPCC-1 macro-region

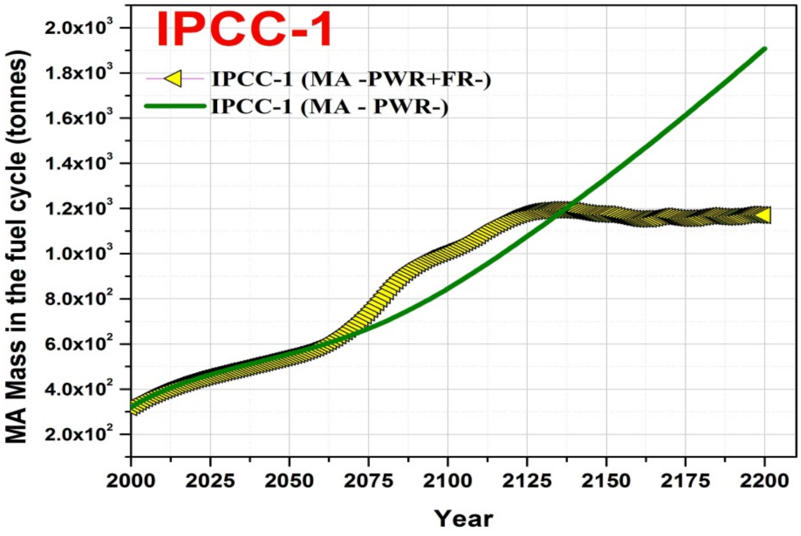


Figure 49: Comparison of the minor actinides (Np+Am+Cm) inventory between the FC option 1 (only PWRs) and the FC option 2 (FRs installed as soon as possible according to Pu availability and 60-year reactor lifetime) in the IPCC-2 macro-region

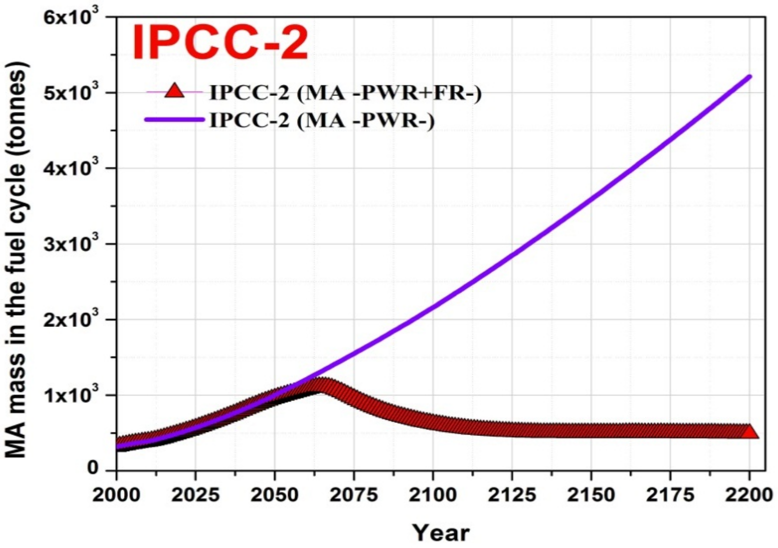


Figure 50: Comparison of the minor actinides (Np+Am+Cm) inventory between the FC option 1 (only PWRs) and the FC option 2 (FRs installed as soon as possible according to Pu availability and 60-year reactor lifetime) in the IPCC-3 macro-region

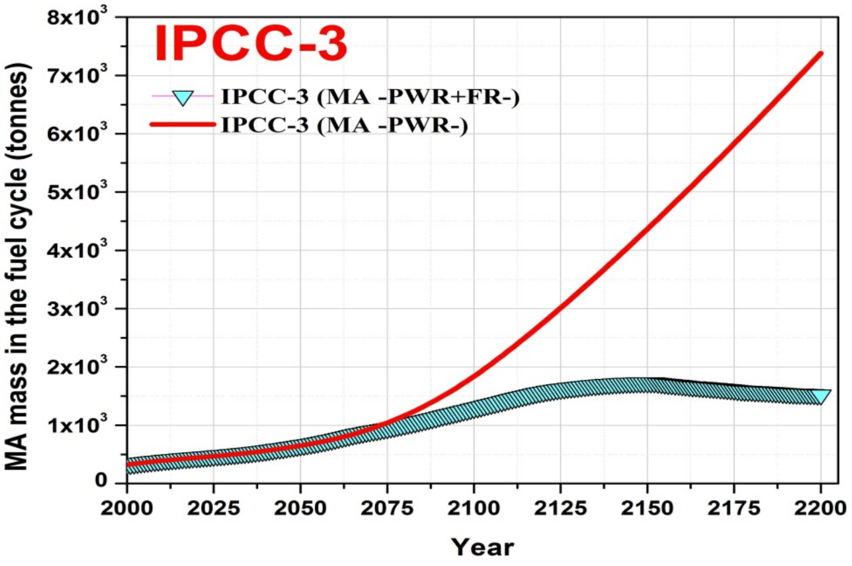
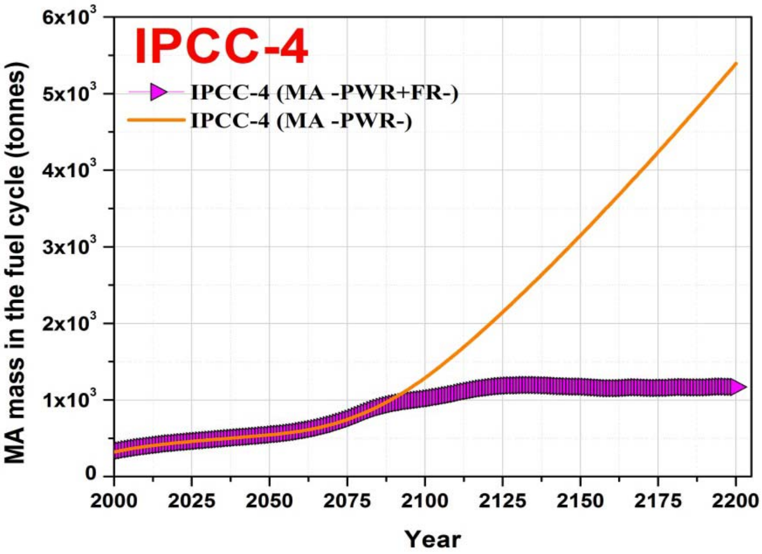


Figure 51: Comparison of the minor actinides (Np+Am+Cm) inventory between the FC option 1 (only PWRs) and the FC option 2 (FRs installed as soon as possible according to Pu availability and 60-year reactor lifetime) in the IPCC-4 macro-region



6. Conclusions

A study of world transition scenarios towards possible future fuel cycles with fast reactors was performed, using both a homogeneous and a heterogeneous approach involving different world regions. The heterogeneous approach considered a subdivision of the world into four main macro-regions (where countries have been grouped together according to their economic development dynamics). An original global electricity production envelope was used in the simulations and specific regional energy shares were defined. In the regional approach, two different fuel cycles were analysed: a once-through LWR cycle was used as the reference and a transition to a fast reactor closed cycle to enable a better management of resources and minimisation of waste.

In this respect, it was shown that the potential future scarcity of uranium resources is not unreasonable, but is a very serious prospect for regions of the world where the energy demand growth is and will very probably continue to be high and where nuclear energy will be employed to at least partially meet that demand. In fact, despite the seriousness of the recent Fukushima Daiichi accident, only a few countries (essentially in the OECD region) have reacted with an abrupt decision to phase out nuclear power. Most countries where the energy demand growth corresponds to an urgent need to achieve widely improved living standards are undertaking extensive reviews of their nuclear programmes, but they are also continuing with ongoing construction projects.

The main objective in both cases (homogeneous or heterogeneous world approaches) was to deploy fast reactors as quickly as possible and to replace the thermal reactor fleet by a fast reactor fleet in order to minimise uranium resource consumption and to cope with steeply increasing global world energy demand. The study has shown that, even with a significant deployment of fast reactors, uranium resources can remain a crucial issue, unless high breeding ratio fast reactors are deployed. In the present study, oxide-fuelled Na-cooled fast reactors with a BR~1.5 (and low doubling times) were considered. This trend points to the potential need to develop and deploy fast reactors with an even higher BR, as it could be in principle obtained with dense fuels and in particular with metal fuel and Na cooling.

The results of this study are obviously very much related to the hypotheses made, in particular in terms of energy demand growth. However, some general trends seem to be of a general value and can motivate further studies.

It was confirmed in this investigation that a rapid development of fast reactors, especially in areas with rapidly expanding economies and strong energy demand growth, is essential for nuclear energy sustainability, for the global saving of natural uranium resources and for the reduction of high-level waste generation requiring disposal. In the case of an open cycle, increased pressure on the uranium market is to be expected towards the end of the current century. Moreover, the increase in mining needs of unequally distributed resources is a factor of uncertainty which may have a large impact on important uranium cost considerations.

It will, however, be a very significant challenge to develop suitable fuel cycle infrastructure especially in the world regions that presently have a limited number of (or no) nuclear power plants. In fact, the needed fuel fabrication and spent fuel reprocessing capacities will be required to increase by at least one order of magnitude over the next decades.

Fuel cycle facilities for uranium extraction, enrichment, fabrication, reprocessing, storage of spent fuel and retrieved fissionable material must be technologically feasible and successively built in order to efficiently manage the swiftly increasing fuel supply required for a rapid transition to fast reactors.

However, the issue of the deployment of a very large reprocessing capacity underlines the potential difficulties of a practical implementation. Regional strategies (see e.g. [33]) for the fuel cycle could help to concentrate specific fuel cycle facilities in only a limited number of countries, despite the fact that challenging institutional and transport problems could arise.

Under the hypothesis of this study, use of fast breeder reactors is indispensable if one tries to provide a global world perspective; their composite doubling time, as indicated above, represents a key parameter in determining the deployment pace.

Of course, in well-developed regions of the world, where a more modest increase in the energy demand is expected, the deployment of fast reactors and their commissioning date are more debatable, as is the assessment of an optimum value of the conversion ratio for these reactors and their potential contribution to waste management.

The support of a thermal reactor fleet in the mix will in all cases be needed until the end of the present century and even beyond independent of the reactor type and global or regional Pu mass availability.

This study should be considered as a preliminary attempt to associate quantified impacts with foreseeable nuclear energy development. It gives some guidelines for performing future studies to account for a wider range of hypotheses on energy demand growth, different hypotheses regarding uranium (and thorium, although it was not considered in the present study) resource availability and different types of reactors to be deployed (e.g. high conversion ratio light water reactors, or innovative once-through reactors with improved uranium utilisation, for example).

Finally, the findings of the present study will have to be compared to other similar ongoing studies (e.g. in the framework of the IAEA INPRO initiative).

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