Sustainability **2012**, *4*, 1214-1238; doi:10.3390/su4061214

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Sustainable Nuclear Fuel Cycles and World Regional Issues

Vincenzo Romanello [1,*], Massimo Salvatores [1,2], Aleksandra Schwenk-Ferrero [1], Fabrizio Gabrielli [1], Barbara Vezzoni [1], Andrei Rineiski [1] and Concetta Fazio [1]

[1] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany; E-Mails: massimo.salvatores@kit.edu (M.S.); aleksandra.schwenk-ferrero@kit.edu (A.S.-F.); fabrizio.gabrielli@kit.edu (F.G.); barbara.vezzoni@kit.edu (B.V.); andrei.rineiski@kit.edu (A.R.); concetta.fazio@kit.edu (C.F.)

[2] Commissariat à l'Energie Atomique (CEA), Cadarache, St-Paul-Lez-Durance 13108, France

* Author to whom correspondence should be addressed; E-Mail: vincenzo.romanello@kit.edu; Tel.: +49-721-608-23406; Fax: +49-721-608-23824.

Received: 27 March 2012; in revised form: 3 May 2012 / Accepted: 29 May 2012 / Published: 12 June 2012

Abstract: In the present paper we have attempted to associate quantified impacts with a forecasted nuclear energy development in different world regions, under a range of hypotheses on the energy demand growth. It gives results in terms of availability of uranium resources, required deployment of fuel cycle facilities and reactor types. In particular, the need to achieve short doubling times with future fast reactors is investigated and quantified in specific world regions. It has been found that a crucial feature of any world scenario study is to provide not only trends for an idealized "homogeneous" description of the global world, but also trends for different regions in the world. These regions may be selected using rather simple criteria (mostly of a geographical type), in order to apply different hypotheses for energy demand growth, fuel cycle strategies and the implementation of various reactor types for the different regions. This approach was an attempt to avoid focusing on selected countries, in particular on those where no new significant 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 the world energy development in the future.

Keywords: sustainability; uranium resources; fast breeder reactors; breeding ratio; world scenario

1. Introduction

Today, 436 nuclear reactors are operational in the world, and 63 are under construction, providing a significant share of electricity 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].

A significant increase in nuclear energy demand is predicted in the next few years, and consequently some important issues about uranium resources and availability of infrastructures are likely to result, within a frame of enhanced safety requirements.

Future fuel cycles characteristics, feasibility and acceptability will be crucial for any foreseeable development of nuclear energy. In fact, despite the seriousness of the recent Fukushima accident, only a few countries (essentially in the OECD "region") have reacted with an abrupt decision to phase out nuclear energy. Most of the countries where the energy demand growth corresponds to an urgent need to achieve widely improved living standards, have launched or completed deep reviews of their nuclear programs, but they are also continuing on-going construction projects. Fuel cycle choices have both long and short term impacts and a holistic assessment of their characteristics, cost and associated safety issues is of paramount importance.

The implications of world transition from current open (or partially closed) fuel cycles (FC) towards future sustainable closed cycles and R&D needs and relevant technology requirements have been explored by the NEA/OECD [3] and IAEA [4].

Different FC options were proposed and many studies have been performed worldwide, see e.g., [5–8]; however the present work was 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 utilization in some countries, such as India, for example [9,10].

In the frame of the NEA/OECD *Expert Group on Fuel Cycle Transition Scenarios Studies*, a simulation of world transition scenario towards possible future fuel cycles with fast reactors has been performed, using both homogeneous and heterogeneous approaches with respect to treating 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 idealized "homogeneous" description of the world, but also trends for its different regions, selected with rather simple criteria (mostly of geographical type), in order to apply, in these regions, different hypotheses on nuclear energy demand growth, different fuel cycle strategies and different reactor types.

This approach helps to provide trends and conclusions that account for specific features of countries that will be major future players in world energy development.

The heterogeneous approach considers 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.

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 the generation 3 (or 3+) reactors, such as modern Pressurized Water Reactors (PWRs), 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 investigations on the impact of the gradual introduction of advanced fuel cycles based on closed cycles and fast neutron reactors.

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

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

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

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

The present paper gives the most important results of the study. More numerical details can be found in [11].

2. Nuclear Energy Demand Hypotheses for the World Study

The main parameters considered in the nuclear energy development scenario have been the availability of natural uranium resources, the nuclear generation capacity growth rate (considering global and regional trends) and the type of reactors considered in the transition scenario (thermal and fast neutron, self-sustaining or breeder, systems).

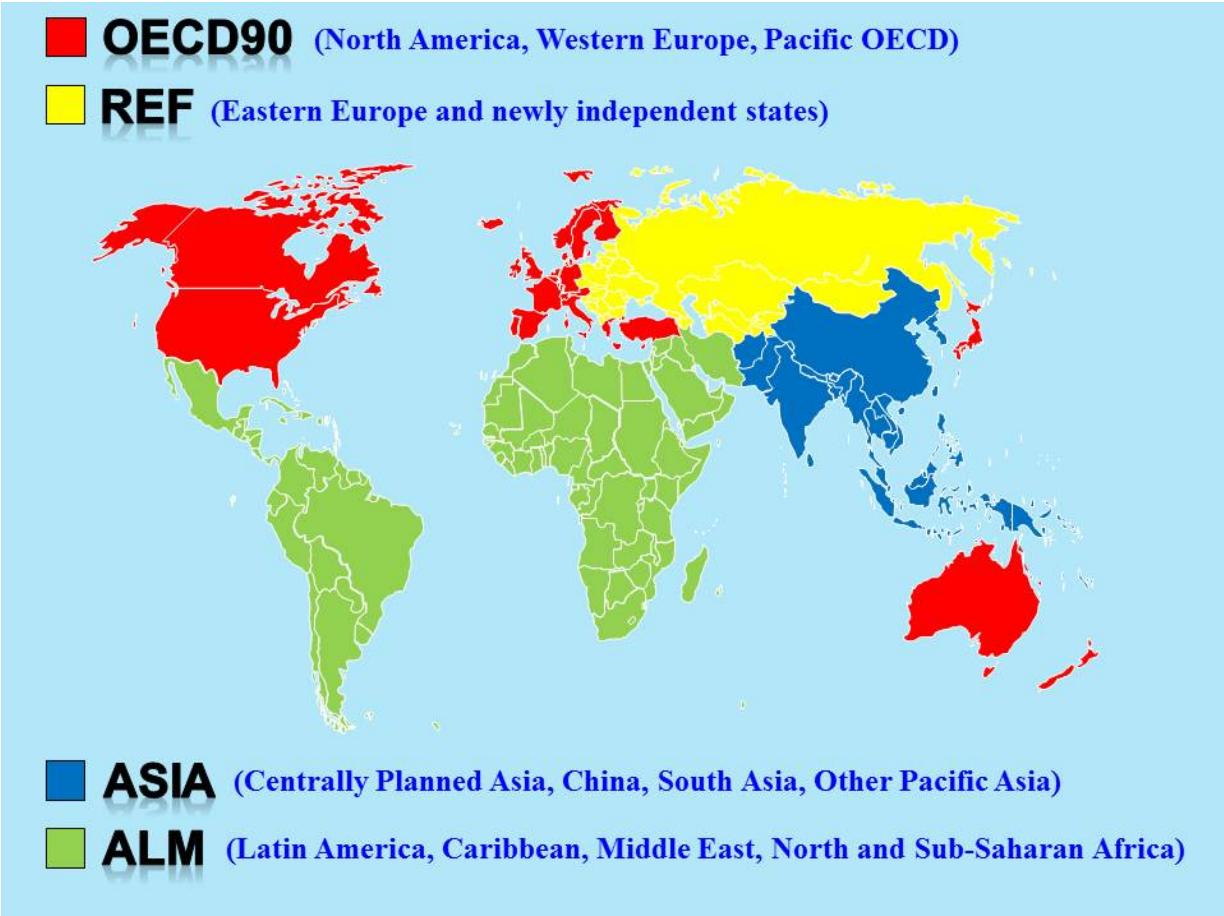
For the "homogeneous world" study, the total nuclear energy envelope provided by Intergovernmental Panel on Climate Change (IPCC—namely, the *"B2-MiniCAM" scenario*, [12]) has been adopted. The same total envelope has been applied for the heterogeneous study. In order to characterize each region (by the definition of the initial conditions), a world subdivision has been adopted. The International Institute for Applied Systems Analysis (IIASA) adopts a refined subdivision in 11 groups successively collapsed in three macro-regions (*i.e.*, industrialized countries, reforming economy countries and the developing countries) [13]. The IPCC adopts the same subdivision but with a different way of collapsing in macro-regions [12]. The IPCC subdivision is indicated in Figure 1.

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

- **OECD90** composed by North America (NAM), Western Europe (WEU) and Pacific OECD (PAO).

- **REF** composed by Central and Eastern Europe (EEU) and newly independent states of the former Soviet Union (FSU).
- **ASIA** composed by Centrally Planned Asia and China (CPA), South Asia (SAS) and Other Pacific Asia (PAS).
- **ALM** composed by Latin America and the Caribbean (LAM), Middle East and North Africa (MEA) and Sub-Saharan Africa.

Figure 1. The adopted world subdivision in regions.



The total nuclear energy projection proposed (see Figure 2) shows a reasonable increase towards the end of the century (ca. 6 times the energy production in 2010), with a higher increase rate 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 [14]).

This global trend, applied to the world homogeneous study, is in agreement with the trend considered by the IAEA dedicated study project [3] in which nuclear energy maintains its current (as of 2007) share of electricity generation (about 14% of global electricity supply).

As for the heterogeneous world study, the energy demand trends for the different regions have been adapted from [13] (regional subdivision proposed by the *Middle course "B"* IIASA scenario [15]) and are shown in Figure 3. For the period 2100–2200, a slight increase of 0.25% per year has been assumed [11].

Figure 2. World Nuclear Energy Projections (TWh_e).

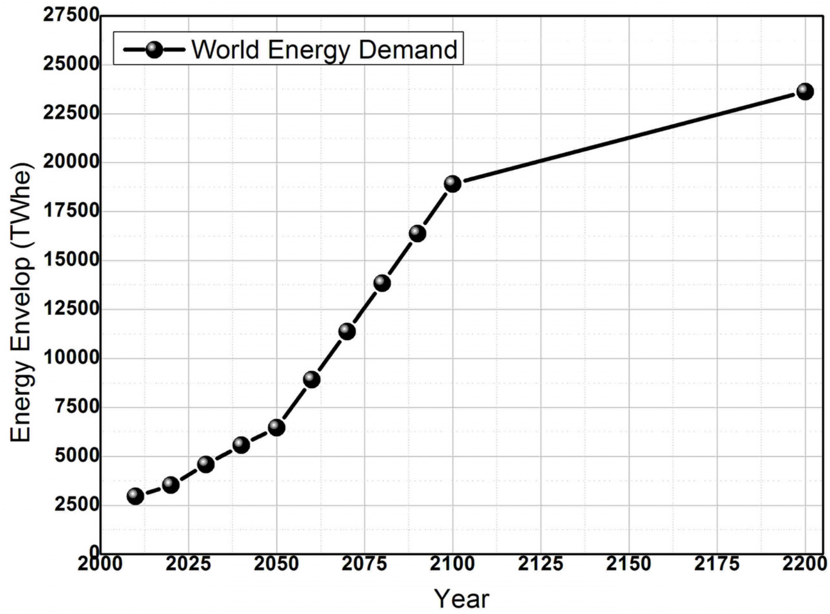
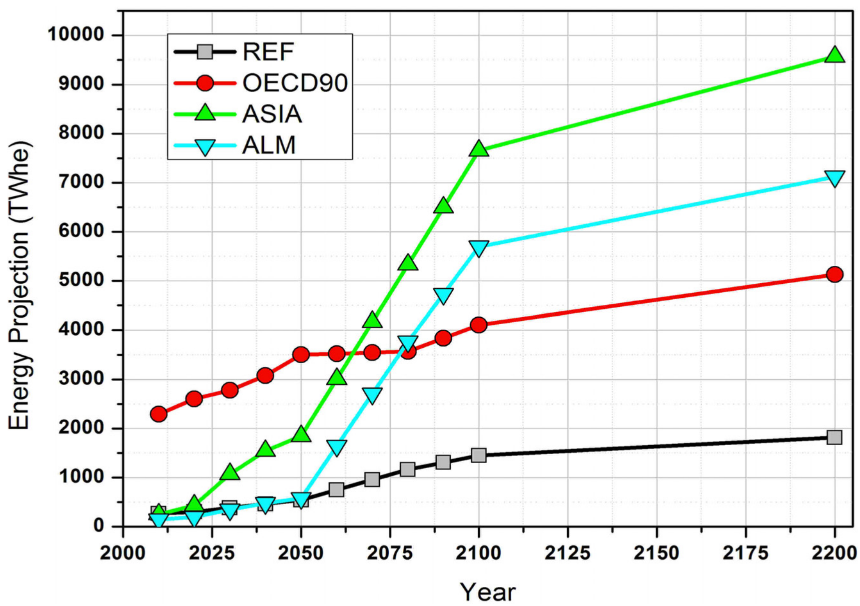


Figure 3. Nuclear Energy Projections (TWhe) per region. B-IIASA subdivision [13] rescaled to the reference scenario total value, derived from [12], see text.



The energy growth trends shown in Figure 3 are somewhat expected for the ASIA region in view of, e.g., recent declarations of the Indian government that do support this trend. As for the ALM regions, they do include countries like Brazil and Argentina with a significant growth potential and countries in the Middle East (e.g., United Arab Emirates and Kingdom of Saudi Arabia) that have foreseen very aggressive plans for nuclear energy deployment in a relatively short/medium term.

For OECD90 and REF regions the trends considered are less pronounced than for ALM and ASIA regions. This behavior is expected considering the lower population growth rate (one of the drivers of the IIASA and IPCC energy trends) and the industrialization level already achieved in these regions.

3. Reactor Models

The COSI6 scenario code has been used for the studies presented in this paper [16]. The code database includes nuclear data libraries, both for thermal and fast neutron reactors. However, it was necessary to develop a new library for breeder systems in order to cope with the 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 French PWR, with fuel assemblies consisting of an array of 17 × 17 fuel pins, with a power of 1,000 MWe (fuel enrichment and burnup are case-dependent).

Two types of oxide fueled fast reactors cores were used: (a) a reactor with a breeding ratio (BR) close to one, for which data have been already presented in the COSI6 database and widely adopted by CEA, e.g., [17]; (b) a fast breeder reactor, with a high breeding ratio to address the energy demand in fast growing regions [18].

This breeder reactor is a Na-cooled fast system with a BR ~1.45 and with reduced doubling time (~11.7 y and 17.8 y, for two different ex-core lag times, respectively). It is useful to recall here that there are several definitions for doubling time: in this study we refer to the composite doubling time as the time required for a fleet to produce enough fissile material for a new startup core (taking into account reprocessing and fabrication) [19]. The COSI code in combination with the reactor models described in Table 1 have been used to model the transition period to optimize the material management, the resource consumption, and the fuel cycle infrastructures: reprocessing, and fabrication capacities, including possible impact on high level waste repositories. Data for the different reactor types are shown in Table 1, where EFPD means effective power days, MA means Minor Actinides, TRU means transuranics, *i.e.*, plutonium (Pu) and MAs. However, for our purposes it was sufficient to introduce a fast reactor which in principle could provide the needed high BR. As for multirecycle, no limit is expected in the case of FRs, since the Pu vector deterioration (*i.e.*, decrease of the Pu fissile) is rather limited. Pu recycle in PWR is limited to two-three recycles for a standard PWR-MOX design. This limit can be practically eliminated if specific PWR-MOX concepts are implemented (see e.g., [20]).

Table 1. Summary of reactors characteristics.

	PWR	ISOGENERATOR	BREEDER
Burnup (GWd/tHM)	50	136	78
Cooling time (years)	5	2	2/5
U235 enrichment or Pu content (%)	4.5	21.19	15.8 [a]/21.2 [b]
Electrical nominal power (GWe)	1	1.45	0.56
Thermal efficiency (%)	34	40	40
Load factor (%)	85	85	85
Breeding or conversion ratio	0.38	1.02	1.45
Cycle length (EFPD)	410	340	300
Fuel irradiation time (EFPD)	1640	1700	2100
Fuel type	UO_2	$(U\text{-}TRU)O_2/UO_2$	$(U\text{-}TRU)O_2/UO_2$
Radial blanket irradiation time (EFPD)	-	2720	2400
MA/Pu mass ratio	-	0.1	0.1

[a]: inner core; [b]: outer core

The chosen breeder design based on oxide fuel does not necessarily represent an optimal way to achieve a high breeding ratio; in fact, dense fuels (like metal ones) could be a better choice [19]. 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 [21] with the JEF2.2 evaluated nuclear data library [22].

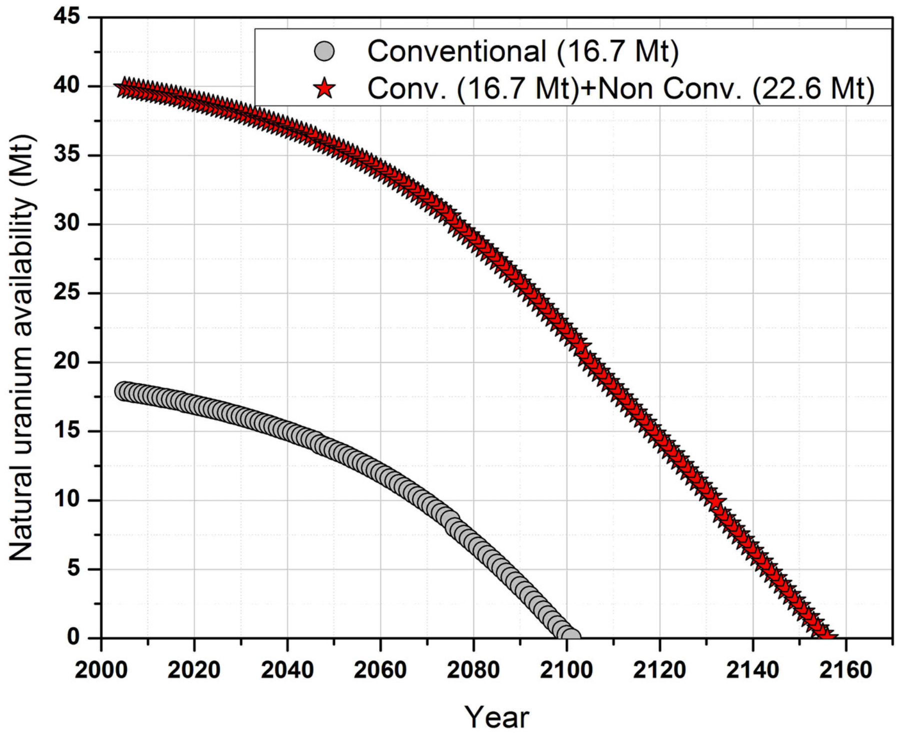
4. Homogeneous World Scenario: PWRs to Meet Energy Demand

The reference case studied considers that the world nuclear energy demand (Figure 2) is met by PWRs only (4.2% enrichment and 50 GWd/tHM burnup). In this scenario plutonium is mono-recycled (a reprocessing capacity of 5,000 t/y was assumed) and used for fabrication of MOX fuels up to 2030 to cover 5% of the total nuclear energy demand.

After 2030, only UOX fuel is used in order to save plutonium resources for possible future use in fast systems.

For the PWR-based fuel cycle, COSI6 simulations show that the conventional uranium resources, defined according to [23], will be exhausted by the end of the present century, while the non-conventional ones will run out at around ~2150 (Figure 4).

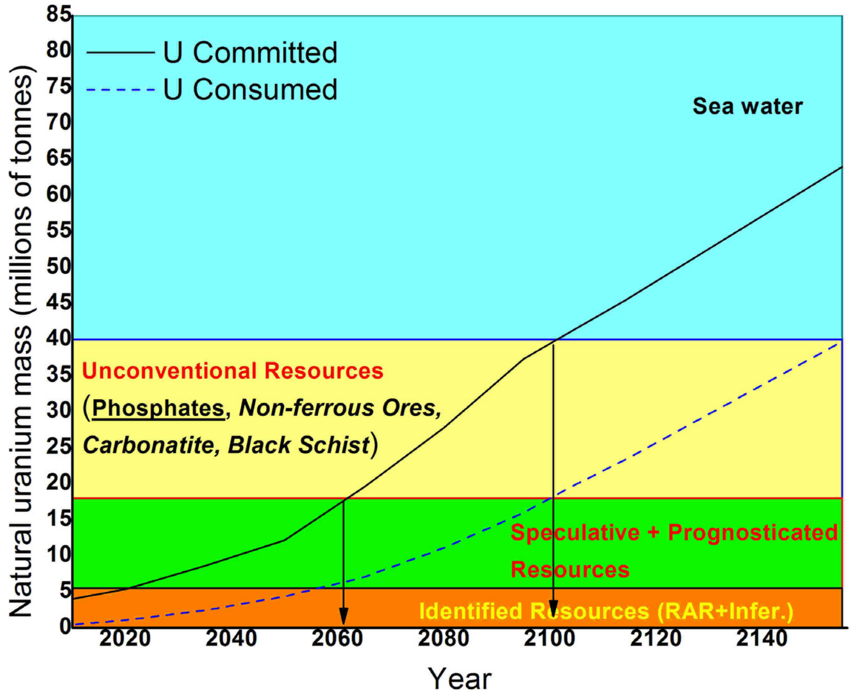
Figure 4. Natural uranium availability *vs.* time for pressurized water reactors (PWRs) once-through case.



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 5). Of course, the overall picture can be more complex in practice.

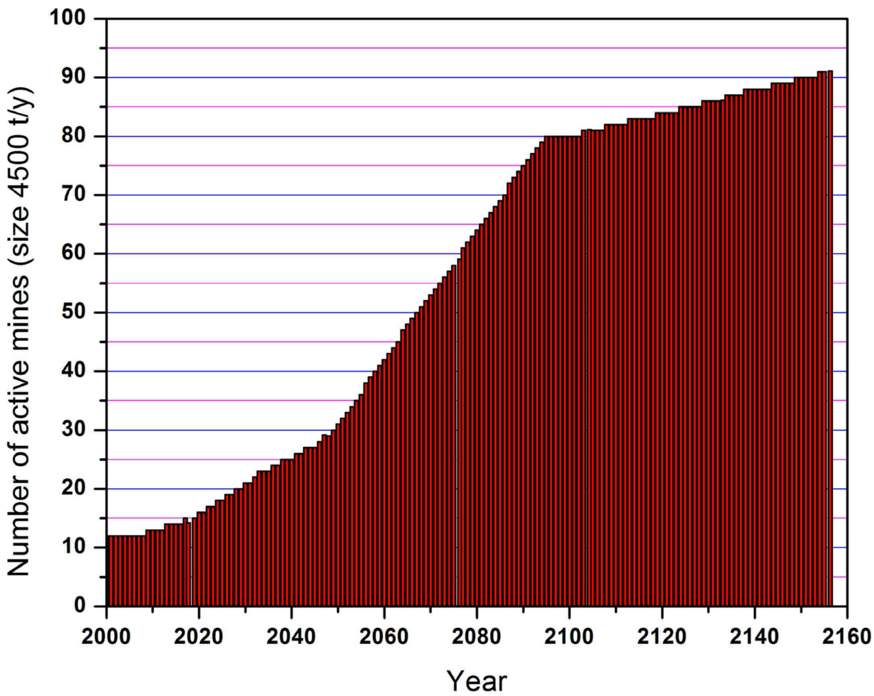
In fact, it should be recognized that identified resources could increase over time as mining companies under demand and market pressure could step up exploring, even if the cost could rise somewhat.

Figure 5. Natural uranium consumed and engaged for PWRs once-through case.



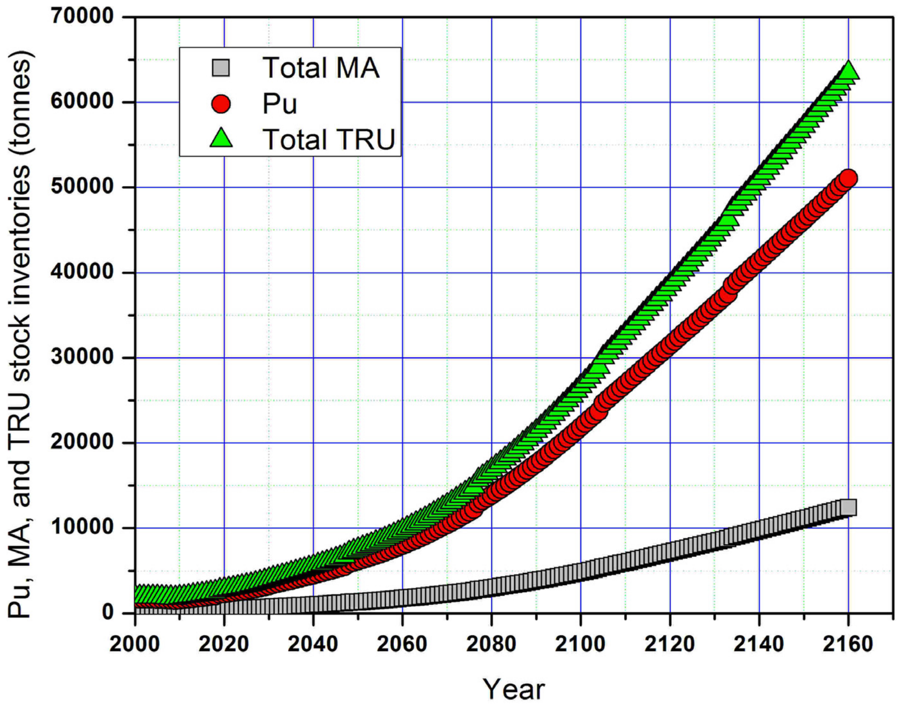
As a consequence of a once-through world fuel cycle, a large amount of spent fuel will accumulate worldwide. The spent fuel composition in 2150 corresponds to roughly 65,000 tons of transuranic elements, which contain ca. 50,000 tons of plutonium and ca. 11,000 tons of MA (Figure 6). It is interesting to note that the adoption of higher burnup values does not significantly affect the results [11].

Figure 6. Plutonium (Pu), MAs and TRUs inventories for PWRs once-through case.



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 to be opened and operated worldwide, potentially posing some significant infrastructural issues. In Figure 7 an estimation of the number of mines to be open is shown (as "unit of measure", the extraction capacity of 4,500 t/year has been adopted).

Figure 7. Number of uranium mines (large size: 4500 t/y) *versus* time required for PWRs once-through case.



5. World Transition Scenario towards Advanced Fuel Cycles

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 Section 4 a world scenario model was discussed, in which the adopted energy demand was met by only PWRs. It was shown that if engaged uranium, *i.e.*, the uranium mass needed to fabricate fuel for PWR start up cores and for refueling of PWRs during their complete operational time, is taken into account, stress on the conventional uranium resources could appear already by ~2060, whereas the unconventional uranium resource limit will be reached at the end of the century. Dedicated simulations showed that no significant differences would result in case of MOX fuels use in PWRs.

In order to address potential future uranium resource shortages, different transition scenarios have been analyzed, see, e.g., [6,23–25]. These scenarios help to evaluate various strategies envisaged for the future of nuclear energy including the transition from an open PWR based fuel cycle to a closed fuel cycle with fast reactors.

In our study, for the closed fuel cycle scenario, a dynamic model of the nuclear energy system has been considered. The system consists of a mix of PWRs and fast breeder reactors, with a progressive replacement of PWRs by fast reactors (FRs), according to the resources availability. The PWRs in this scenario are fuelled with uranium oxide, and the FRs are loaded with fuel containing depleted uranium (from uranium enrichment facilities) and recovered TRU from reprocessing. In order to accumulate plutonium needed for FR deployment as soon as possible, no recycling of plutonium in PWRs has been considered. The transition from a system dominated by a once-through cycle to a closed cycle based on FRs with multi-recycling will most likely span over several decades. An important aspect is to determine the maximum deployed capacity of FRs that is consistent with sustainable development and also the fraction of energy produced by the supporting thermal fleet. The deployment pace of isogenerators depends on the plutonium mass recovered from light water reactor spent nuclear fuel and thus requires increased fuel reprocessing and fabrication capacities. Moreover, fuel ex-core lag time, affects the pace of new FR reactor introduction and consequently influences the resource consumption [6]. The increase of fuel reprocessing and fabrication is mainly due to the requirements of emerging countries, as it will be shown in the following paragraphs. In fact, the infrastructure increase in the OECD countries will be much more limited, as will be discussed later on. This result is in agreement with the findings of a recent study devoted to European scenarios [26]. As a starting point, the simplified homogeneous world approach was chosen (Pu and MA initial stockpile was considered according to elaboration from available literature data [27]). The pace of deployment of FRs 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 subassemblies are put back into fast cores. The mass of generated plutonium in FRs depends on the breeding ratio (BR), where BR is defined as the rate of plutonium production from fertile isotopes divided by the rate of plutonium consumption. High breeding ratio implies that more fissile material is produced than destroyed, thus, it shortens the transition (from PWRs to FRs) period length and reduces therefore 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 ("isogenerator") and BR~1.45. In the first case, a sodium-cooled FR with a near unity BR, European Fast Reactor (EFR) was used, see Table 1. The reactor core is loaded with MOX fuel containing depleted uranium and plutonium (with a small fraction of MA, mainly Am-241). Near unity BR fast reactors could be a viable option in national and even regional transition scenarios driven by a constant energy demand or a low nuclear energy growth rate [24,25].

The deployment pace of isogenerators depends on the plutonium mass recovered from light water reactor spent nuclear fuel and thus requires increased fuel reprocessing and fabrication capacities. Moreover, fuel ex-core lag time affects the pace of new FR reactor introduction and consequently influences the resource consumption [6].

Advanced high breeding ratio FRs (with design characteristics described in Section 3) were also considered. This option applies to fast developing world regions with a high nuclear energy demand growth rate and lacking 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 analyzed scenarios span over nearly two centuries; the reference period is 2010–2200. Under the hypothesis that both the breeder and the isogenerator FR technologies could be ready for industrial deployment by 2050, this date was chosen in both cases as the beginning of the transition period. The fuel ex-core lag time in these simulations includes fuel cooling, reprocessing and fabrication time. It was chosen to be 5 years for high performance breeder reactors, resulting in a composite doubling time (CDT) of 17.8 years. In order to achieve a faster growth, the composite doubling time was reduced to 11.7 years by imposing a shorter ex-core lag time (equal to 2 years). The sum of the cooling and reprocessing times for discharged subassemblies of radial and axial fertile blankets was assumed to be 2 years as well.

Spent fuel from PWRs was cooled 5 years before reprocessing. 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. TRU losses and all fission products were assumed to go to a high level waste interim storage. Finally, a reactor lifetime of 60 years was considered in simulations.

The outcome of the simulation studies in terms of annual nuclear electric energy production, expressed in TWhe, per installed reactor class is given in Figures 8 and 9. In case of isogenerators, only a slow stepwise deployment schedule is possible due to shortages in the supply of recovered plutonium needed to fuel startup cores. In periods when FR energy production is kept constant the surplus of plutonium necessary to add new units is generated mainly by PWRs. The plutonium mass produced in fertile blankets is added to the stockpile, but at the end of the next century a thermal reactor share of 23% is still necessary to cover the nuclear energy demand. The share of fast systems in the fleet in 2100 is around 26% (isogenerators), 75% (fast breeders with CDT~18 y), and 80% (fast breeders with CDT~12 y), respectively.

Figure 8. Nuclear energy production of fast reactor fleet.

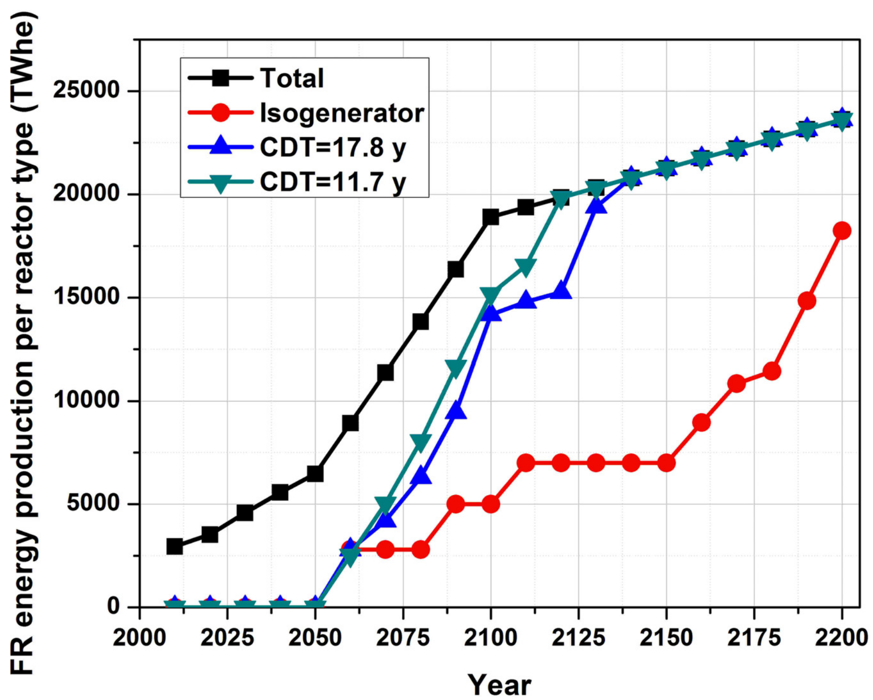
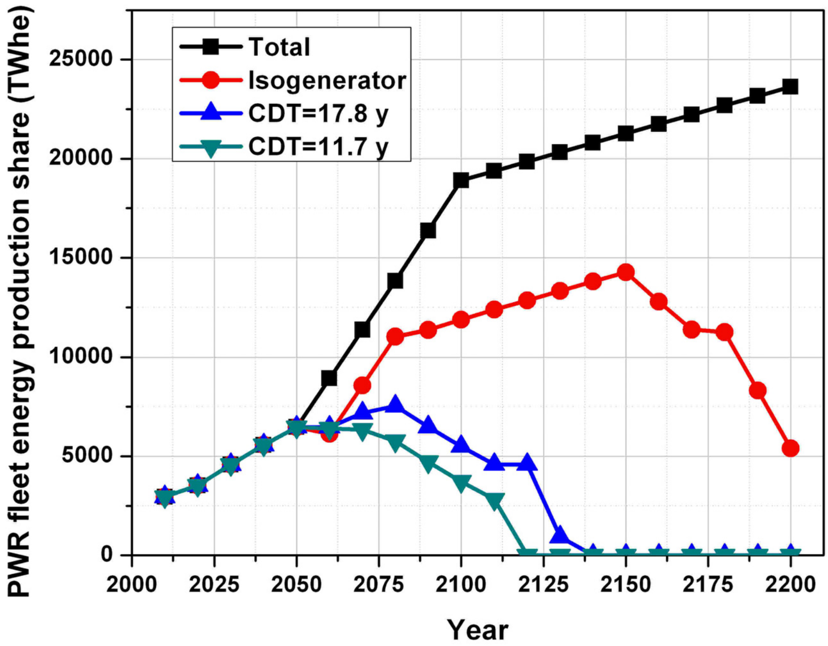


Figure 9. Nuclear energy production of supporting PWR fleet.



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

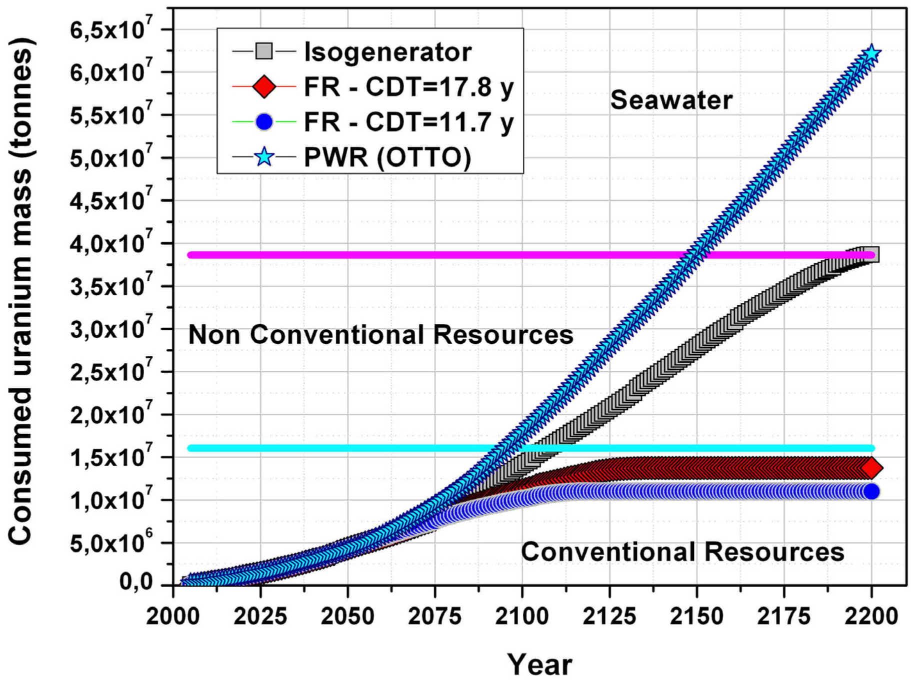
(a) 2140–2200 if longer composite doubling time (~18 years) is postulated;
(b) 2120–2200 if a shorter doubling time (~12 years) is assumed.

Simulation results indicate that for both FR introduction options, PWRs remain a significant part of the reactor system until the end of the present century due to the assumed nuclear energy demand which exhibits a very steep slope in the time period 2050–2100. Of course, the spent fuel inventory available for reprocessing, the composite doubling time (dependent on fuel ex-core time) and the fast reactor breeding ratio represent key parameters.

Different FR options lead to different cumulative masses of consumed natural uranium. As shown in Figure 10, significant reductions of the consumed uranium mass with respect to the PWR once-through fuel cycle can be achieved (OTTO means Once Through Then Out and stands for PWR open cycle without spent fuel reprocessing). This mass remains below the conventional uranium resource limit if high BR fast reactors are deployed. In contrast, deploying isogenerators causes an exhaustion of conventional resources in ~2110 and of unconventional resources in 2200.

According to scenario hypotheses for high performance breeders, a gradual decrease of reprocessing and fabrication capacities *vs.* time for UOX fuel is expected together with an increased need for FRs fuels. The required throughput (capacities) of FR fuel facilities closely follow the imposed nuclear energy demand curve. It has been found that the deployment of both isogenerators and strong breeders will require an increase by at least a factor of 7 of the current reprocessing capacities for PWR spent fuel in the time period 2025–2050 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 by the end of the present century. It has to be pointed out, however, that in the present study the adoption of enriched uranium as an alternative to plutonium was not considered, although some studies [6] showed that it can reduce requirements on reprocessing infrastructures and fissile material availability, at least in an initial phase. However, this option would not allow us to save uranium resources, as required by the goals of the scenarios here investigated, and should pose further pressure on enrichment plants development due to a higher capacity and enrichment requirements, with possible further proliferation concerns.

Figure 10. Mass of consumed uranium *vs.* time for different fast reactor classes.



6. World Scenario: Regional Approach

6.1. Scenario with PWRs Only

The homogeneous world scenario does not take into account potential differences in nuclear energy demands, technology development and required rates of deployment in different regions. For this reason an additional study was performed in which the world was split into four macro-regions, namely OECD90, REF, ASIA and ALM, as discussed previously.

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

- OECD90 and REF deploy fast reactors (*"isogenerators"*, *i.e.*, breeding ratio close to one) in 2040;
- ASIA and ALM deploy high performance breeder reactors starting from 2060 and 2080, respectively.

ASIA and ALM deploy high performance breeder reactors starting from 2060 and 2080, respectively. The delay in deployment with respect to deployment date of fast reactors in the OECD countries has been introduced to account in a very approximate manner for the need of a longer development time in countries that have a significantly lower experience in that type of technology.

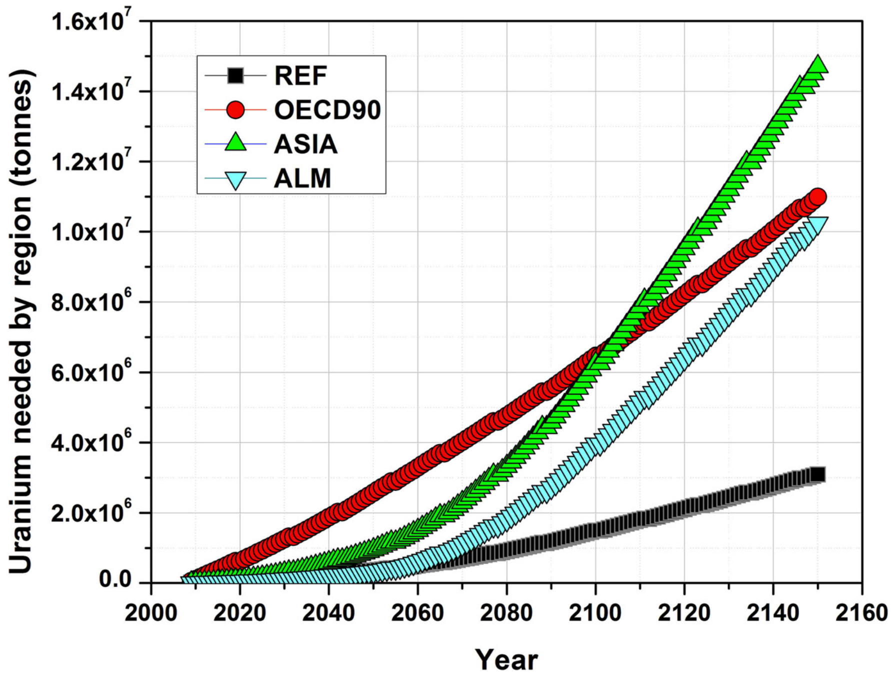
If one of the important objectives is to save the maximum amount of natural uranium resources, a strategy of replacing the thermal reactor fleet by fast reactors in the shortest time period allowed by plutonium availability should be adopted.

The nuclear energy production envelopes have been described in Section 2 and it was assumed that there would be an unrestricted access to uranium between macro-regions, according to demand, while enriched fuel and reprocessed materials could not 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: OECD90 ~83%, REF ~10%, ASIA ~6%, and ALM ~1% [27].

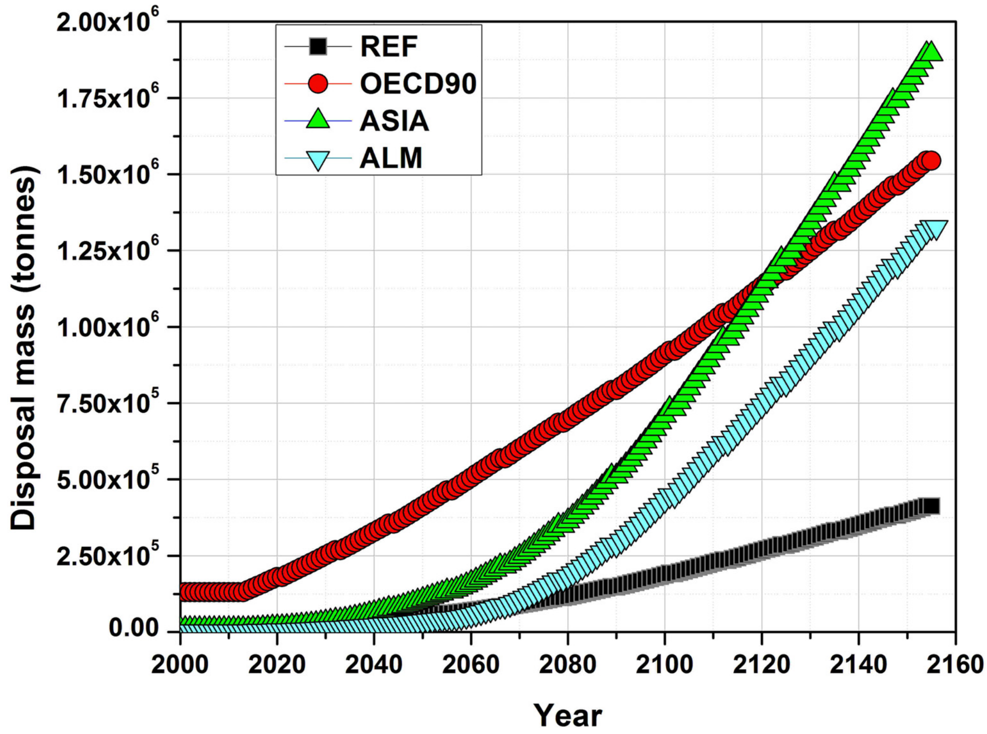
Figure 11 shows the uranium mass requirements for each region as a function of time. The highest demand is in ASIA (*ca*. 15 million tons), followed by OECD90 and ALM (*ca.* 10–11 million tons). It is relevant to note that ASIA will match the OECD90 uranium requirement at the end of the century and it will significantly exceed it afterwards. Finally, at the time of the exhaustion of resources, REF, OECD90, ASIA and ALM 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 ASIA should be forced to import heavily, as they own only 5% of the global uranium resources.

Figure 11. Cumulative consumed natural uranium masses subdivided per macro-region (case: only PWRs deployed).



The spent fuel inventory masses to be disposed as a function of time up to year 2150 are given in Figure 12.

Figure 12. Spent fuel mass inventories per region (case: only PWRs deployed).



The transition from a regional scenario based only on the once-through PWR 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. 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 shown later. 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 with the largest growth rates (*i.e.*, ASIA and ALM).

6.2. Fast Systems and Closed Fuel Cycles

In Figures 13–16 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 are the outcome of an optimization process, of which the main objective was to develop fast fleets as soon as possible in order to obtain the best exploitation of uranium resources.

As discussed previously, in the ASIA and ALM regions (Figures 13 and 14), high performance breeder reactors (*i.e.*, with short composite doubling times) were chosen to cope with the assumed high nuclear energy demand and growth rates. In OECD90 and REF regions (Figures 15 and 16), isogenerators were used, with their deployment beginning in 2040. The use of FRs with different breeding ratios in the different world macro-regions is mainly driven by the nuclear energy demand growing rates, which are very fast growing in developing regions, according to the hypotheses. In OECD90 and REF countries, where a lower increase of nuclear energy demand is expected, the deployment of isogenerator fast reactors represents probably a more reasonable choice, see e.g., [4].

Figure 13. Nuclear energy production share in ASIA (PWRs and breeders).

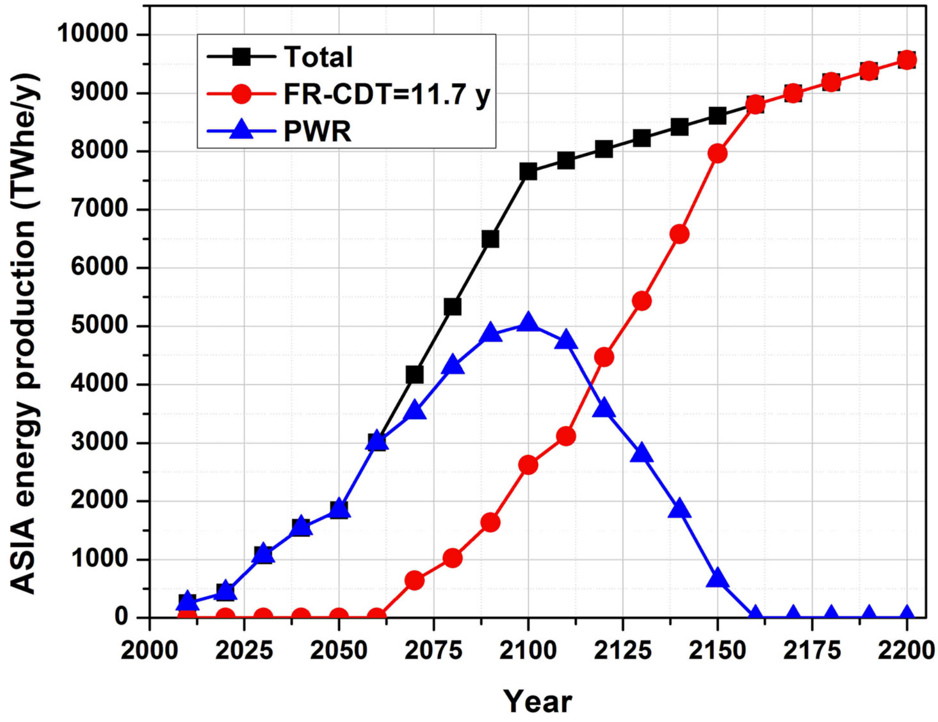


Figure 14. Nuclear energy production share in ALM (PWRs and breeders).

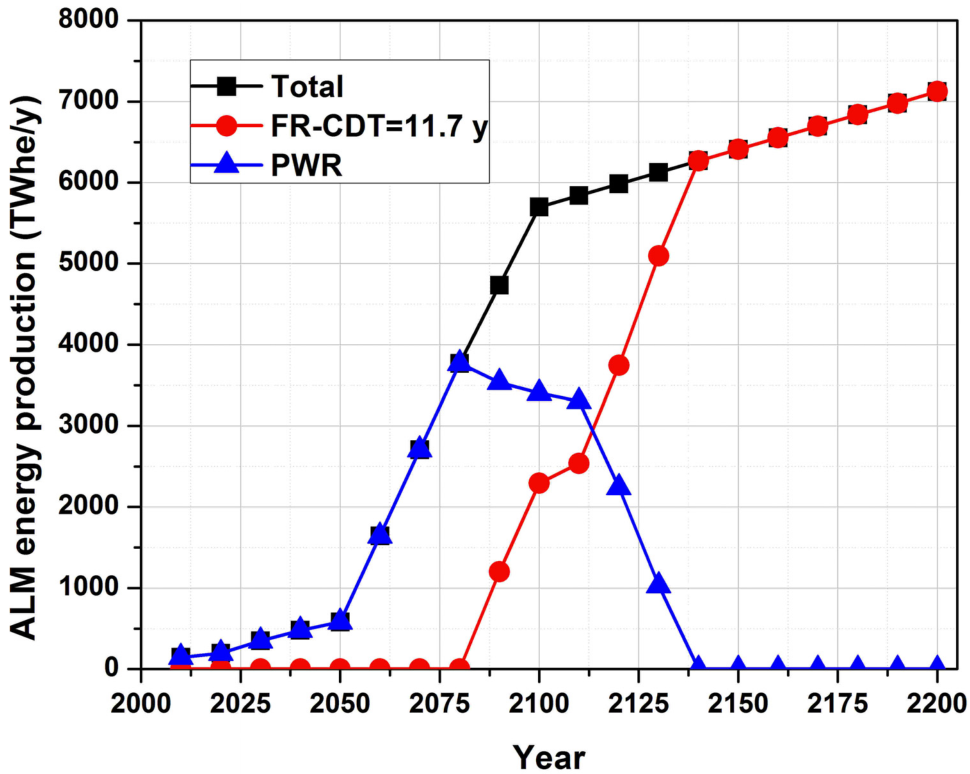


Figure 15. Nuclear energy production share in OECD90 (PWRs and isogenerators).

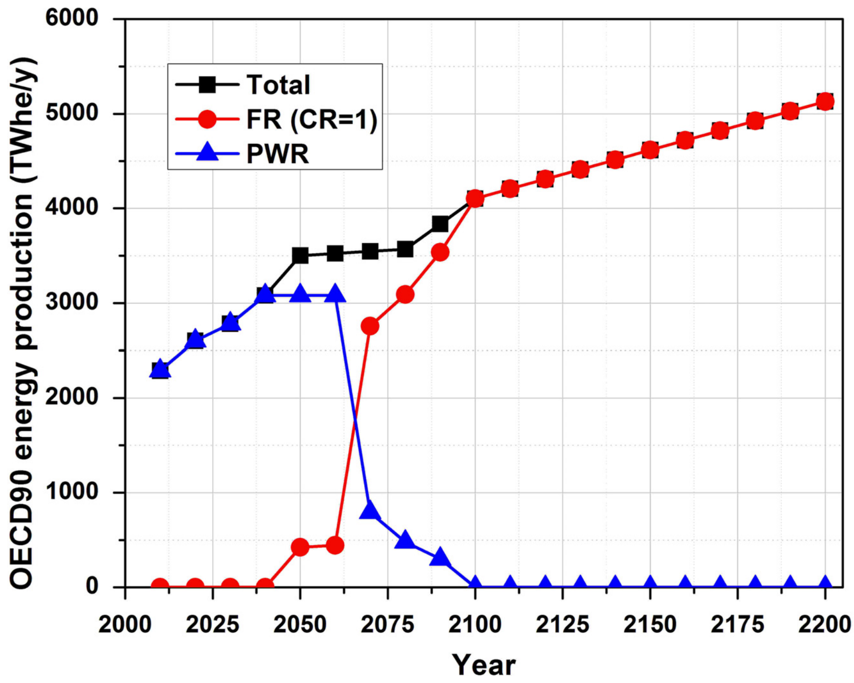


Figure 16. Nuclear energy production share in REF (PWRs and isogenerators).

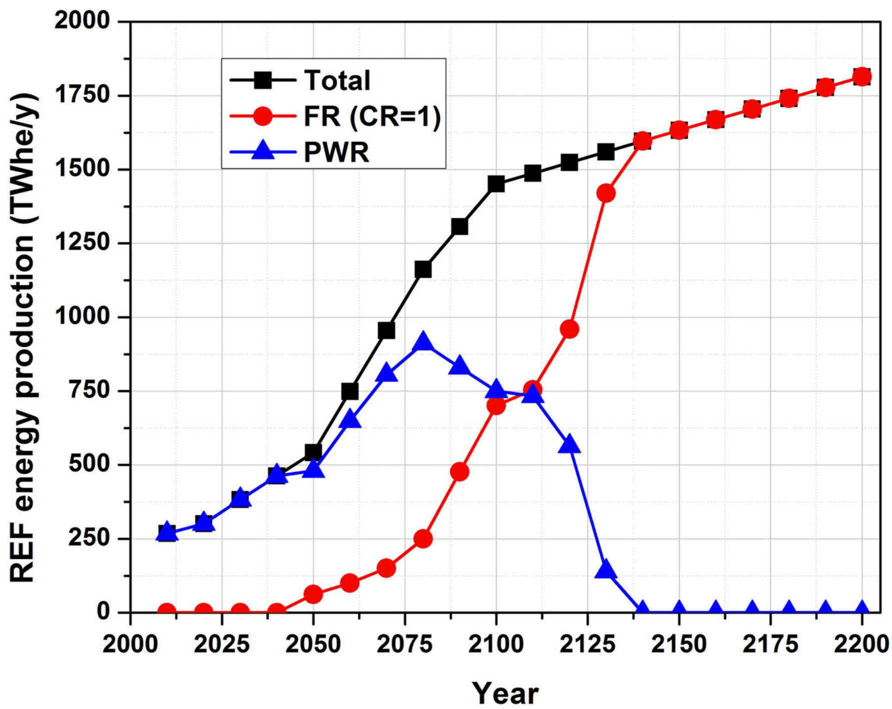
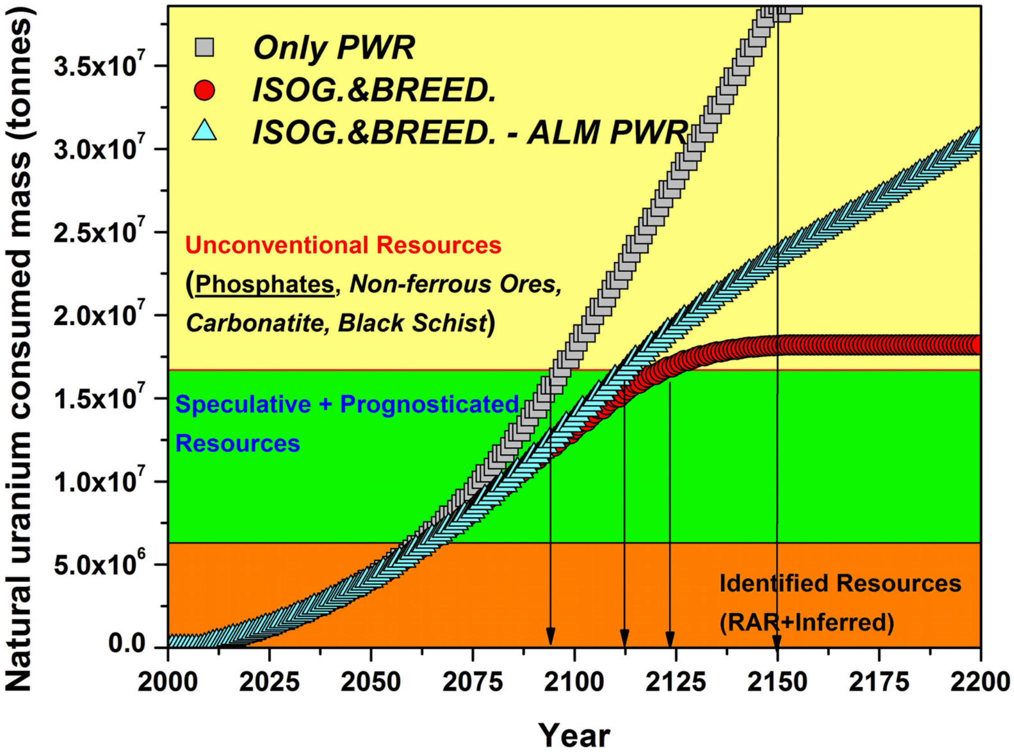


Figure 17 shows the variation of natural uranium consumption rate with time for three fuel cycle options: (1) ***PWRs "once-through"*** fuel cycle, (2) the ***PWRs transition to FRs in all world regions***, and (3) the ***PWRs transition to FR in all regions except ALM*** where, in the hypothesis of a much more delayed deployment of FR, the nuclear energy needs are met only by PWRs operating in an open cycle.

Figure 17. Total natural uranium consumptions for three different deployment scenarios (***PWRs lifetime 60 years assumed***): (■) Fuel Cycle option 1: only PWRs with open cycle; (●) option 2: ASIA and ALM (breeders) + OECD90 and REF (isogenerators) (▲) option 3: ASIA (breeders) + OECD90 + REF (isogenerator) + ALM (only PWRs).



For the once-through option 1, the natural uranium resources (*i.e.*, identified + speculative and prognosticated + unconventional) will run out at ~2150 and other type of uranium resources such as seawater must eventually be exploited. Otherwise, by adopting fast neutron systems (according to plutonium availability) in all regions (option 2), the use of unconventional resources (*i.e.*, phosphates rocks, carbonatite, black schist, lignite, *etc.*) will be only marginal.

Finally, if only ALM adopt thermal reactor systems only and all other regions make a transition to fast systems, unconventional resources will have to be exploited around 2110–2120.

The increase of both fuel fabrication and of reprocessing capacities will be significant and a large increase in capacity of these facilities will be required in fast growing regions (ASIA and ALM). In fact, ASIA and ALM will require a UOX fabrication capacity of ~10,000 tons by ~2067 and ~2077 respectively, while in the OECD90 countries that capacity will reach ~10,000 tons 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: ~4000 tons in the OECD countries by ~2090; ~18,000 tons in ASIA by ~2140 and ~14,000 tons by ~2130 in the ALM group of countries.

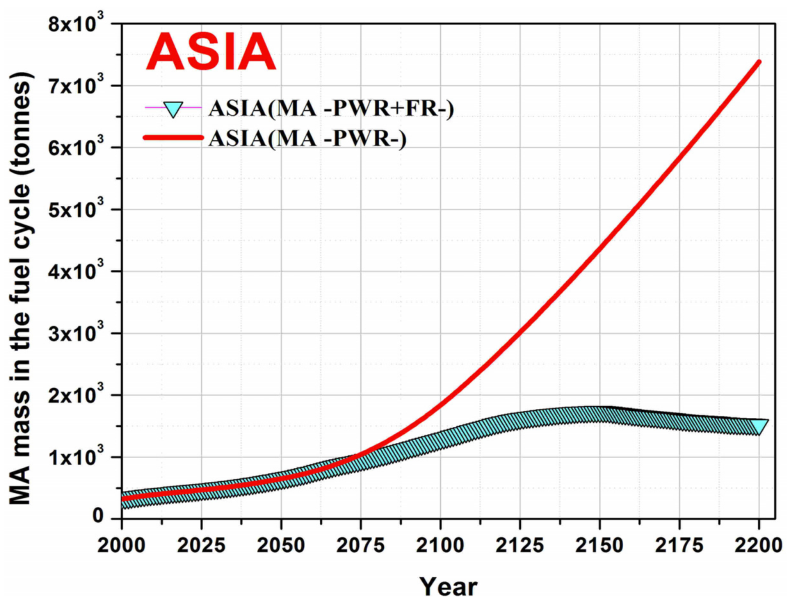
When compared with the existing world annual reprocessing capacity (mostly in the OECD countries) *i.e.*, ~3800 tons/year, a value of ~6 times higher is expected in ASIA and a value of ~4 times higher in ALM by ~2130, while an increase by a factor of ~2–3 is expected by ~2050 in the OECD countries. In practice, this would mean that the ALM and ASIA reprocessing capacities should be increased by about 1130 tons/year every 10 years (*i.e.*, equivalent to the development of a La Hague-size reprocessing plant every 15 years). Potential infrastructure growth issues are likely to occur, particularly in ASIA and ALM together with less aggressive deployment pace. In contrast to the homogeneous scenario, no PWRs are required in 2200 in the regional approach. Faster deployment pace of breeders in ASIA and ALM regions is possible due to the high breeding ratio and short doubling time of FR type used in the scenario simulations. In OECD90 and REF regions there is enough plutonium recovered from spent PWR fuel to accelerate the deployment pace of isogenerators which are able to cover fully the total energy demand from 2100 or 2140, respectively.

6.3. Impacts on the Back-End of the Fuel Cycle

As for the impact of the different scenarios on some parameters of interest for the back-end of the fuel cycle, some general issues related to the build-up of MA in the fuel cycle, the heat load and the radiotoxicity in a geological disposal have been here considered. No specific hypothesis on a regional final disposal facility has been made. It has been simply considered for this preliminary investigation that the regional geological disposal is a "dump" for all spent fuels, in the case of the once-through option, or of the losses at reprocessing in the case of close fuel cycle. In both cases, the disposal initial date is the year 2200.

As a further simplification, results associated to MA only, taken as one indication of potential repository issues are discussed. As an example, Figure 18 gives the trends of MA build-up in the ASIA region. The stabilization in the case of closed fuel cycle with MA recycle is clearly shown. It has to be pointed out that in the case of the closed fuel cycle with fast reactors option, the largest mass of minor actinides is continuously recycled within the fuel cycle, while only fission products and reprocessing losses are stored before being sent to the geological disposal. The reduction of the overall MA inventory by 2200 is by a factor ~6–7.

Figure 18. Comparison of the Minor Actinides (Np+ Am+Cm) inventory between the once-through (option 1, *i.e.*, only PWRs are deployed) and the closed fuel cycle option (option 2: FRs installed as soon as possible according to plutonium availability) in the ASIA region.



In Figures 19 and 20, a comparison of the radiotoxic inventory and heat load (both associated here also only to the MA inventory) between the once-through and the closed fuel cycle (with fast reactors) options is presented. The reduction is in both cases very significant, *i.e.*, at least two orders of magnitude with respect to the once-through fuel cycle option. This result is related to the amount of MA sent to the repository. This amount in the case of the closed fuel cycle corresponds to only a fraction of the full MA inventory in the fuel cycle, shown in Figure 18.

Figure 19. Comparison of the radiotoxic inventory (ingestion) in a geological disposal for the ASIA region between the once-through and the closed fuel cycle options (only the MA component is displayed).

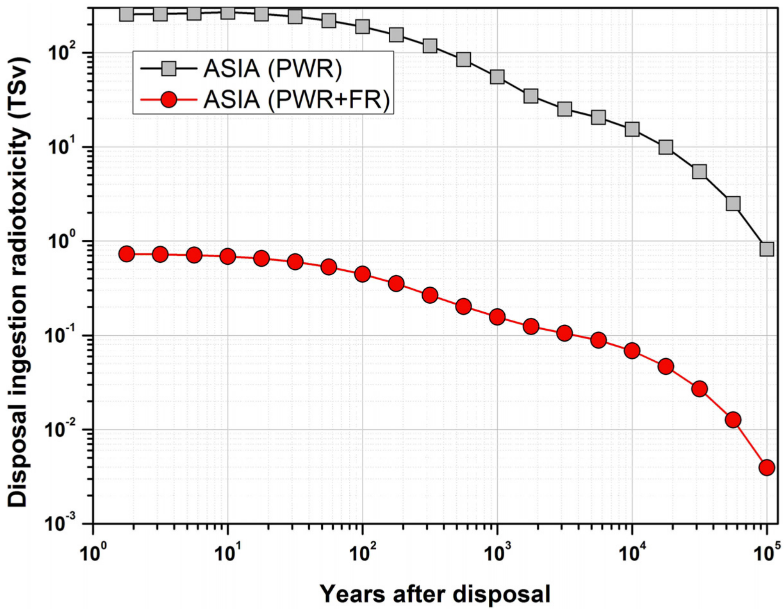
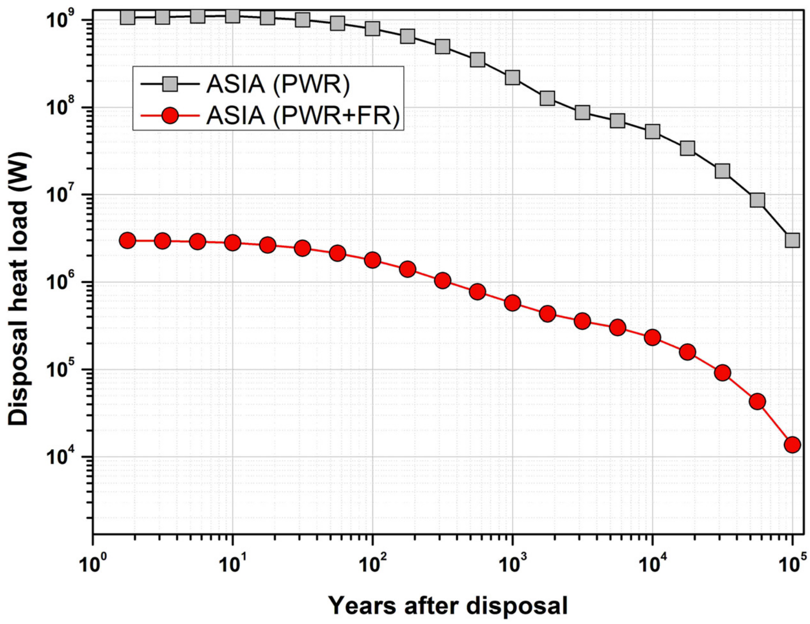
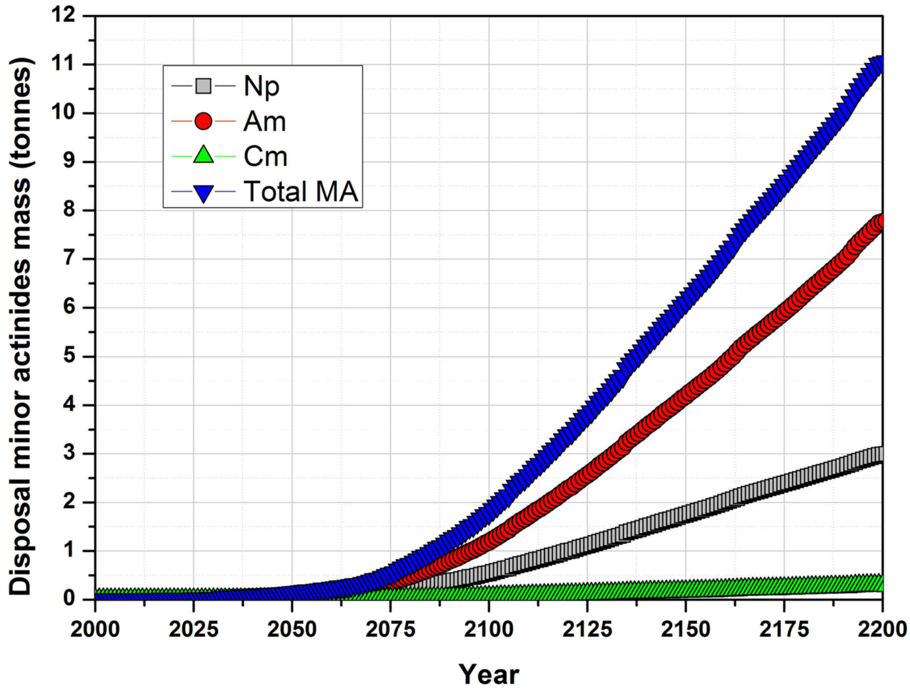


Figure 20. Comparison of the heat load in a geological disposal for the ASIA region between the once-through and the close fuel cycle options (only the MA component is displayed).



In fact, Figure 21 shows both the total amount of MA losses build-up versus time in the closed fuel cycle scenario and also the relative neptunium, americium, and curium shares in the MA inventory.

Figure 21. Total amount and share of MA to be sent to a geological disposal in the ASIA region *versus* time for the closed cycle option.



The reduction is directly associated to the built-up MA loss inventory (~11 tons by 2200, decontamination factor at reprocessing 10^{-3}) which has to be compared to the built-up MA inventory at the same date in case of the once through cycle (~7.5 10^{3} tons).

These results indicate that for the waste minimization issue, large gains are related to the deployment of closed fuel cycles with the use of fast reactors associated also to MA recycling. These gains may have a significant impact on the waste repository performances, since one could envisage the reduction of the needed repositories, the reduction of the performance uncertainties and the reduction of the potential abnormal evolution (e.g., human intrusion) consequences [28]. As for geological repository footprint, a reduction of a factor in the range 3 to 9 can be expected, as an extrapolation from previous studies for comparable scenarios applied to single world regions (see e.g., [29]), would suggest.

7. Conclusions

A study of world transition scenarios towards possible future fuel cycles with fast reactors was performed. COSI6, developed by CEA (France), was used for simulations, which provide mass, radiotoxicity and heat load inventories with a discrete approach (*i.e.*, keeping into account real charge-discharge process of physical stocks). It is important however to remember that at present all scenario codes provide "nominal" values and uncertainties are not treated systematically: however, new activities have been initiated under the OECD-NEA Working Party on Fuel Cycle issues (WPFC) that should contribute to the uncertainty assessment. In this study, both homogeneous (world as one region) and heterogeneous approaches involving different world regions were adopted. The heterogeneous approach considers a subdivision of the world into four main macro-regions. A global nuclear energy production growth hypothesis, derived from reference studies, has been adopted and a specific regional nuclear energy share has been considered. Two different fuel cycles were analyzed: a once-through PWR cycle was used as the reference, and a transition to a fast reactor closed cycle has been investigated to enable a potentially better management of resources and minimization of wastes.

In this respect, it was shown that the potential future scarcity of uranium resources can be a serious issue for regions of the world where the energy demand growth is and will very probably continue to be high, and where nuclear energy is widely expected to at least partially meet that demand. In fact, despite the seriousness of the recent Fukushima accident, only a few countries (essentially in the OECD "region") have reacted with an abrupt decision to phase out nuclear power. Most of the countries where the energy demand growth corresponds to an urgent need to achieve widely improved living standards, are certainly making deep reviews of their nuclear programs and in particular of the safety requirements, but are also continuing on-going construction projects.

The main objective in both cases studied, *i.e.*, homogeneous or heterogeneous world approaches, was to deploy fast reactors as rapidly as possible and to replace the thermal reactor fleet by a fast reactor fleet in order to minimize the 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, the 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~1.45 (and low doubling times) were considered. This trend points out 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 global saving of natural uranium resources and for reducing high level waste generation requiring disposal. In the case of an open cycle, an increased pressure on the uranium market is to be expected towards the end of the current century. Moreover, the increase of mining needs of unequally distributed resources is a factor of uncertainty which may have an important impact on uranium cost considerations.

It will be, however, a very significant challenge to develop suitable fuel cycle infrastructure especially in the world regions that presently have limited (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, and 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., [30]) for the fuel cycle could help to concentrate specific fuel cycle facilities in only a limited number of countries considerably reducing proliferation concerns, despite the fact that challenging institutional and transport problems could arise.

A further potential reduction of the proliferation concern could be a widespread adoption of reprocessing techniques that do not allow the separation of plutonium from MA.

As for the waste minimization issue, large gains are expected with the deployment of closed fuel cycles and the use of fast reactors. These gains can have a significant impact on the waste repository performances, since one could envisage the reduction of the needed repositories, the reduction of the performance uncertainties and the reduction of the potential abnormal evolution (e.g., human intrusion) consequences.

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 of 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, independently of the reactor type and global or regional plutonium mass availability.

This study should be considered as a preliminary attempt to associate quantified impacts to a foreseeable nuclear energy development. It gives some guidelines to perform future studies that could consider different hypotheses for the energy demand growth, different hypotheses on the uranium (and thorium, which was not considered in the present study) resource availability, and different type of reactors to be deployed, as well as the technological readiness of innovative fuel cycle facilities.

Conflict of Interest

The authors declare no conflict of interest.

References

1. Weisser, D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* **2007**, *32*, 1543–1559.
2. IEA and NEA. *Projected Costs of Generating Electricity—2010 Edition*; International Energy Agency: Paris, France, 2010; ISBN: 978-92-64-08430-8.
3. NEA. *Nuclear Fuel Cycle Transition Scenario Studies*; NEA/OECD Report No. 6194; Paris, France, 2009.
4. IAEA. *Nuclear Energy Development in 21st Century: Global Scenarios and Regional Trends*; No. NP-T-1.8; IAEA: Vienna, Austria, 2010.

5. Baschwitz, A.; Loaëc, C.; Fournier, J.; Delpech, M.; Legée, F. Long Term Prospective on the Electronuclear Fleet: From Gen II to Gen IV. In *Proceedings of the GLOBAL 2009*, Paris, France, 6–11 September 2009.
6. Massara, S.; Tetart, P.; Lecarpentier, D.; Garzenne, C. Prospective scenarios for nuclear energy evolution on the XXIst century over the world scale. *Nucl. Eng. Des.* **2009**, *239*, 1708–1717.
7. Xu, M. Status and Prospects of Sustainable Nuclear Power Supply in China. In *Proceedings of the GLOBAL 2005*, Tsukuba, Japan, 9–13 October 2005.
8. Shiotani, H.; Ono, K.; Namba, T. Characteristic Evaluation and Scenario Study on Fast Reactor Cycle in Japan. In *Nuclear Power–Deployment, Operation and Sustainability*; Tsvetkov, P., Ed.; InTech: Rijeka, Croatia, 2011. Available online: http://www.intechopen.com/books/nuclear-power-deployment-operation-and-sustainability/characteristic-evaluation-and-scenario-study-on-fast-reactor-cycle-in-japan (accessed on 11 June 2012).
9. Anantharaman, K.; Shivakumar, V.; Saha, D. Utilization of thorium in reactors. *J. Nucl. Mater.* **2008**, *383*, 119–121.
10. Rodriguez, P.; Bhoje, S.B. The FBR program in India. *Energy* **1998**, *23*, 629–636.
11. OECD-NEA. *Transition Towards a Sustainable Nuclear Fuel Cycle: A World Scenario Analysis*; NEA: Paris, France, in press.
12. IPCC. *Special Report on Emissions Scenarios*; IPCC: Geneva, Switzerland, 2000; ISBN: 92-9169-113-5.
13. IIASA. *Global Energy Perspectives*; Cambridge University Press: Cambridge, UK, 1998; ISBN: 0-521-64569-7.
14. IAEA. *Energy, Electricity and Nuclear Power Estimates for the Period Up to 2030*; IAEA: Vienna, Austria, 2009; ISBN: 978-92-0-109809-2.
15. IIASA database. Global Energy Perspectives. Available online: http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py (accessed on 23 March 2012).
16. Boucher, L.; Grouiller, J.-P. COSI: The Complete Renewal of the Simulation Software for the Fuel Cycle Analysis. In *Proceedings of the 14th International Conference on Nuclear Engineering (ICONE14)*, Miami, FL, USA, 17–20 July 2006.
17. Lefèvre, J.C.; Mitchell, C.H.; Hubert, G. European fast reactor design. *Nucl. Eng. Des.* **1996**, *162*, 133–143.
18. Romanello, V.; Salvatores, M.; Schwenk-Ferrero, A.; Gabrielli, F.; Maschek, W.; Vezzoni, B. Comparative study of fast critical burner reactors and subcritical accelerator driven systems and the impact on transuranics inventory in a regional fuel cycle. *Nucl. Eng. Des.* **2011**, *241*, 433–443.
19. Waltar, A.E.; Reynolds, A.B. *Fast Breeder Reactors*; Pergamon Press: Oxford, MI, USA, 1980.
20. Youinou, G.; Vasile, A. Plutonium multirecling in standard PWRs loaded with evolutionary fuels. *Nucl. Sci. Eng.* **2005**, *151*, 25–45.
21. Rimpault, G.; Plisson, D.; Tommasi, J.; Jacqmin, R.; Rieunier, J.M.; Verrier, D.; Biron, D. The ERANOS Code and Data System for Fast Reactor Neutronic Analyses. In *Proceedings of the PHYSOR 2002*, Seoul, Korea, 7–10 October 2002.
22. Nuclear Energy Agency. *The JEF-2.2 NDA. JEFF OECD NEA Report 17*; Nuclear Energy Agency: Paris, France, 2000.

23. NEA/OECD and IAEA. *Uranium 2009: Resources, Production and Demand*; OECD: Paris, France: 2010; ISBN: 9264047891.
24. MIT. *The Future of the Nuclear Fuel Cycle. An Interdisciplinary MIT Study*; Summary Report; Massachusetts Institute of Technology: Cambridge, MA, USA, 2010; ISBN: 978-0-9828008-1-2.
25. United Nations Development Program. Human Development Report 2010. Available online: http://hdr.undp.org/en/media/HDR_2010_EN_Complete_reprint.pdf (accessed on 23 March 2012).
26. von Lensa, W.; Nabbi, R.; Rossbach, M. *RED-IMPACT, Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal*; Synthesis Report; Forschungszentrum Jülich GmbH: Jülich, Germany, 2007; ISBN: 978-3-89336-538-8.
27. IEA-OECD. Energy to 2050–Scenarios for a Sustainable Future. Available online: http://www.oecd-ilibrary.org/energy/energy-to-2050-scenarios-for-a-sustainable-future_9789264019058-en (accessed on 31 May 2012).
28. Salvatores, M.; Geckeis, H.; Gompper, K.; Marivoet, J.; Milot, J.F.; Oigawa, H.; Saturnin, A.; Taiwo, T.; Wigeland, R.; Zaetta, A. NSC-WPFC Task Force on Potential Benefits and Impacts of Advanced Fuel Cycles with Actinide Partitioning and Transmutation (WPFC/TFPT). In *Proceedings of the International Conference on GLOBAL 2011*, Makuhari, Japan, 11–16 December 2011.
29. Roelofs, F.; Hart, J.; van Heek, A. European new build and fuel cycles in the 21st century. *Nucl. Eng. Des.* **2011**, *241*, 2307–2317.
30. Salvatores, M.; Meyer, M.; Romanello, V.; Boucher, L.; Schwenk-Ferrero, A. Fuel Cycle Synergies and Regional Scenarios. In *Proceedings of the 10th OECD Nuclear Energy Agency Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation*, Mito, Japan, 6–10 October 2008.