Scenarios for a worldwide deployment of nuclear power

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Abstract: The growing worldwide demand for energy must be controlled. However, even in the event of voluntary policies to dampen energy demand, it is hard to imagine that the demand could be less than twice as much as today's by 2050. We feel it is necessary to satisfy this demand. It is obvious also that greenhouse gas emissions must be reduced in order to limit the severe consequences that they entail. An energy shortage could develop if new sources of large-scale energy production are not established. A significant contribution of nuclear power to such energy production by 2050 rests on a well-coordinated and optimised deployment scheme (Loiseaux *et al*., 2004; The Future of Nuclear Power, 2003). This requires, as early as today, a reflection on the present status of nuclear power, on its extrapolation into the future and, thus, on the means that should be put to work and the transition possibilities.

Keywords: nuclear energy production; energy demand evaluation; sustainability; Generation IV; fissile and fertile resources; thorium fuel cycle; molten salt reactor; fast neutron reactor; deployment scenarios.

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Biographical notes: Elsa Merle-Lucotte started as an Assistant Professor at the Ecole Nationale Supérieure de Physique of Grenoble (ENSPG) and joined the Laboratory for Subatomic Physics and Cosmology in the research staff in 2000. Since then, she has been actively involved in the French National Center of Scientific Research (CNRS) programmes dedicated to the conceptual design of innovative Generation IV reactors. As such, she contributes to various studies and validations of the concept of molten salt reactors, through reactor simulations, experimental measurements, and the conception and testing of worldwide electro-nuclear-power-deployment scenarios. At the same time, she is a member of the national organising committee for the Journées Jeunes Chercheurs 2006 (French Society for Physics), dedicated to PhD students in nuclear physics.

Daniel Heuer is a Research Officer in CNRS. Since 1996, he has been involved in the physics of nuclear reactors. An expert in numerical simulations, he developed an innovative software platform aimed at describing the time evolution of the nuclear fuel and inventory of an operating reactor. After studying subcritical reactors, he is now working more specifically on molten salt reactors based on the thorium–U-233 fuel cycle that operates as a power provider as well as minor actinides burner. He is presently a Co-Leader of the CNRS research programme on molten salt reactors, including the nuclear physics, chemistry and engineering departments.

Christian Le Brun obtained his PhD from the University of Caen (France), and is Directeur de Recherche at CNRS and a Senior Physicist with more than 80 publications. He has been involved in and responsible for the conception, realisation and analysis of several experiments in the field of particle and nuclear physics. Since 2000, he has been fully involved in studies of innovative nuclear reactors, such as accelerator-driven reactors and thorium molten salt reactors. He has managed the LPC Caen laboratory and now manages the GEDEPEON research group.

J.M. Loiseaux obtained his doctorate degree in Paris. He spent a year at Lawrence Berkeley Laboratory, doing research devoted to heavy-ion nuclear physics. Then he coordinated the definition and building of a heavy-ion accelerator. From 1993 to 1996, he participated in the FEAT experiment (initiated by C. Rubbia), which demonstrated the feasibility of the Accelerator-Driven Subcritical Reactor (ADSR). He then led a team of ten physicists working on reactor physics for Generation IV nuclear reactors and investigating the thorium cycle using molten salts. For four years, he was Co-Chairman of a French collaborative programme on nuclear waste management and energy production.

1 Introduction

Several major problems at issue motivate the present study: the reserves of ^{235}U, the only natural fissile nucleus, are limited; more intensive production of nuclear power with the current technology could lead to a rapid depletion of the resource. Moreover, the advent of new reactor technologies based on the other two accessible fissile elements, namely plutonium and ^{233}U, requires that the production of these two elements be planned in advance, since they are not naturally available.

The deployment of nuclear power, if it is to be well coordinated and successful, must take many factors in consideration, among which are:

- what will the worldwide energy demand be and, more specifically, to what extent will nuclear power be expected to contribute
- what are the reserves for the resources involved (uranium, thorium) and the stockpiles of fissile material (plutonium, ^{233}U, ...)
- what will the technologies be in the coming years (reactor type, fuel cycle), what are their characteristics and what is the radio-toxicity induced by the wastes generated.

Our aim in this work is to explore the potential for worldwide nuclear power deployment and its limitations. In this view, we pay particular attention to the availability of uranium 235, the only natural fissile element, which is, as a consequence, the major constraining factor in the frame of sustainable development. Secondly, we evaluate the possibility of eventually shutting down the reactor fleets started, taking into consideration only the heavy nuclei whose handling is tricky. The fission products generated are the same in all the deployment scenarios, so that they are not considered in our discussion.

The complex interweaving of the factors and constraints involved has made the use of a dedicated programme necessary. We have developed a parameterised calculation algorithm (Heuer and Merle-Lucotte, 2004) that helps us examine how nuclear power can best respond in a sustainable way to an intense energy demand.

The first section of this paper exposes the data, in terms of energy needs and available resources, on which the rest of the work is based. It also shows how these data are taken into account in the parameterised algorithm we use to evaluate the deployment of nuclear power. The scenarios considered are explained in the subsequent sections, along with the results we have obtained so far, in terms of reactor deployment and resource depletion.

In this paper, the need to produce large amounts of fissile matter will be presented. Such a production, and the degree of breeding, depends a great deal on the technology of the reactors considered. We have used estimations, pending more hardcore data to be obtained from work currently in progress in the French National Center of Scientific Research (CNRS) laboratories. These estimations already give an idea of the constraints that come into play in the deployment of nuclear power.

2 Basic data: energy demand and resource availability

2.1 Energy demand projections

The projected evolution of energy needs that we have selected for our scenarios is inspired from that published by Bauquis (1999). This projects a world population of eight to ten billion by 2050 and takes into account potential restrictions on fossil fuels, in particular oil and gas (see Table 1).

Table 1 Energy need projection until 2050 according to Bauquis

	2000	*2020*	*2050*
Population	6 billion	7.5 billion	8–10 billion
Total primary energy	9.3 GToe	14 GToe	18 GToe
Fossil fuel (oil+gas+coal)	8 GToe	12.2 GToe	12.6 GToe
Share	(85%)	(87%)	(70%)
Renewable + Hydroelectric	0.7 GToe	0.9 GToe	1.4 GToe
Share	(7.5%)	(6.5%)	(8%)
Nuclear power	0.6 GToe	0.9 GToe	4 GToe
Share	(6.5%)	(6.5%)	(22%)

Note: GToe: billion ton oil equivalent

Similar projections can be worked out using a simple formula and making a few assumptions, in particular that of a stabilisation of fossil fuel consumption at its current level. To evaluate the evolution of worldwide energy demand, we can write it as:

$$E = \frac{E}{GNP} * \frac{GNP}{N} * N$$

where:

N = world population
GNP/N = per capita gross national product
E/GNP = energy intensity

According to demographic estimations, the world population should grow from six billion in 2000 to about nine billion in 2050, yielding a 3/2 term in the formula above. The annual economic growth (per capita GNP) is projected to be 1.5% in the more pessimistic scenarios up to 3% in the more optimistic view. The *GNP/N* term is then multiplied by something between 2.1 and 4.4. Energy intensity could induce a factor of 0.5 in the formula above if energy savings are included in this term. The worldwide energy demand could thus double by 2050.

We now need to estimate the share of nuclear power in this worldwide production of energy. We made the following choices:

- to maintain the use of fossil fuels at its current level
- to attribute an equal share of the demand to new renewable energies and to nuclear power.

The resulting energy mix is summarised in Table 2.

Table 2 Contribution of the commercial primary energy sources in 2000 and our projection for 2050

Primary energy	*2000*	*2050*
Fossil fuels	8 GToe	8 GToe
+ Hydroelectric power and new renewables	0.7 GToe	5.3 GToe
Nuclear power	0.6 GToe	5.3 GToe
Total	9.3 GToe	18.6 GToe

These numbers show that the production of nuclear power is multiplied by a factor close to eight by 2050. This is the energy scenario that we have applied in the work we describe below. We would like to stress that such a scenario, which is very optimistic as to the energy savings term and the contribution of the new renewable energies, still does not reduce greenhouse gas emissions, since the contribution of fossil fuels has been stabilised but not reduced. The demand on nuclear power is thus probably underestimated. Similar projections have been found in other studies (Nifenecker *et al.*, 2003; Criqui, 2004).

We now turn our attention to the prospective evolution of nuclear power capacity. All the deployment scenarios described below rest on the target progression given in Table 3: starting at zero in 1970, nuclear power production rises to 1800 tera Watt hours of electric power or TWhe in 1985, to 2400 TWhe in 2000. Nuclear power remains stable from 2000 to 2015, and then increases at the rate of 6.2% per year until 2050, achieving the eightfold increase by 2050; it then slowly increases by 1.1% per year until 2100. Extrapolating up to 2100 allows us to verify that the deployment scenarios are lasting.

Table 3 Projection for nuclear power production up to 2100

1970	*2000*	*2015*	*2050*	*2100*
0 TWhe	2400 TWhe	2800 TWhe	18000 TWhe	32400 TWhe
0 GWe.year	340 GWe.year	400 GWe.year	2570 GWe.year	4630 GWe.year

Note: Terawatt-hour electric (TWhe) units, and gigawatt electric-year (GWe.year) units considering a reactor efficiency of 80%

Sources: Extrapolation from Bauquis (1999), Nifenecker *et al*. (2003) and Criqui (2004)

In the next sections, we simulate the deployment of several reactor technologies and examine how well they satisfy the anticipated energy demand:

- The first simulation relies only on light water reactors.
- The second simulation involves light water reactors and Fast-Neutron Reactors (FNRs) (Merle-Lucotte *et al*., 2004).
- The third simulation involves light water reactors and Molten Salt Reactors (MSRs), which operate with a thermal neutron spectrum and are based on a ^{232}Th -^{233}U fuel cycle.
- Our last simulation involves all the above reactor types – light water reactors, U-Pu-based FNRs and ^{232}Th -^{233}U-based MSRs (Merle-Lucotte *et al*., 2004).

2.2 Natural uranium and thorium resources

Workable natural uranium resources are sorted according to extraction cost. The amount of the resource that has already been extracted is estimated at 2 million metric tonnes of uranium (MtU) (Luciani and Simon, 2002). The established reserves for an extraction cost of \$40/kgU amount to 1.6 MtU; they amount to 2.6 MtU at a cost of \$80/kgU, representing 40 years of consumption at the current level. The estimation of the total natural uranium resource is a function of technology and of the acceptable extraction costs. Today, the average uranium extraction cost is \$30/kgU; extrapolating to an extraction cost of \$400/kgU gives a total amount of 23 MtU (Luciani and Simon, 2002). It is intentionally that we use this optimistic value for the limit on the natural uranium resource in our deployment scenarios. Most authors take 8 to 17 MtU as the limit on the resource (IAEA, 2002).

Just like uranium 238, thorium 232 is a fertile material: it can be converted to uranium 233, which is fissile. Thorium resources are abundant; they are estimated to be twice or three times as large as those of uranium. In our scenarios, however, and because the reactors considered consume a small fraction of the fertile matter in the natural resource, we have set the same limit on the thorium resource and on the uranium resource so that it is easier to compare the evolution of these two quantities.

2.3 Using the basic data in the parameterised calculations

For each year of the deployment simulation, nuclear reactors are started up as needed to satisfy the target energy demand. The type of reactor that is started is chosen as follows:

- the highest-priority reactor type is selected
- the amount of fuel required to operate the reactor during its entire life is calculated
- if enough fuel is available from the stocks at all times during the reactor's lifespan, the reactor is started and this process is repeated until the year's target energy demand is satisfied
- if, at any time in the reactor's lifespan, there is not enough fuel to operate it, fuel-manufacturing units, *i.e.*, enriching and reprocessing units, are started. Two possibilities arise:
  1. The fuel units have enough raw material (natural or produced in other reactors that are already in operation) to manufacture the fuel necessary for the reactor being considered. The reactor is started and the process is pursued with another reactor of the higher-priority type until the target energy demand for the year is satisfied.
  2. The resources needed to manufacture the fuel run out before the end of the reactor's lifespan. The possibility of starting another, lower-priority type of reactor is examined using the same procedure. If no reactor can be started, the target world energy demand is out of reach for the set of reactor types specified and the deployment year concerned.

3 Scenario with light water reactors

In our first scenario, nuclear power production is based solely on reactors in which ordinary water is the moderator and the fuel is based on enriched uranium. This is the prevalent reactor type today. It accounts for 87% of worldwide nuclear power production. The remaining 13% are produced by heavy-water–moderated reactors called CANadian Deuterium Uranium (CANDU) and water-graphite reactors called Graphite Light Water Reactor (GLWR) (ELECNUC, CEA, 2003).

3.1 Reactor types in the scenario

Light water reactors imply a thermal neutron spectrum, ordinary water serving as both moderator and coolant. Two types of light water reactors are involved in our simulation: the Pressurised Water Reactors (PWR) as currently used in France, and the future European Pressurised Reactor (EPR[1]). Their general properties are listed in Table 4.

Table 4 General properties of the light water reactors used in the scenario

	PWR	*EPR*
Output capacity	1.0 GWe	1.45 GWe
Load factor	0.8	0.8
First operating date	1970	2010
Reactor lifespan	40 yrs	50 yrs

3.2 Characteristics of existing light water reactors

In PWRs, the fuel is enriched natural uranium (UOX). The characteristics of the fuel and the amount required per GWe.year of energy produced are given in Table 5, as well as the ensuing wastes.

Table 5 Characteristics of PWR fuel

	PWR
Type of fuel	UOX
^{235}U enriching ratio for the fuel	3.5%
^{235}U enriching ratio of the rejected depleted uranium	0.3%
^{235}U enriching ratio of the fuel unloaded (before fuel reprocessing)	1%
Amount of fuel loaded	27.2 tons
Corresponding amount of depleted uranium	179.8 tons
Corresponding amount of natural uranium	207 tons
Amount of spent fuel after reprocessing	26 tons
Amount of plutonium produced	270 kg

Note: The amounts are given in metric tons and per GWe.year of energy produced

Natural uranium-enriching plants are included in our simulation; they process natural uranium to produce the fuel required for the reactors. The output of these plants is enriched and depleted uranium in the enriching ratios shown in Table 5.

3.3 Characteristics for future light water reactors

For the future EPR, three types of fuel (de Saint Jean *et al*., 2000; Youinou *et al*., 2003; Merle-Lucotte *et al*., 2004) were considered, in order to evaluate the impact the fuel option can have on the nuclear-power-deployment scenarios (see Table 6):

1. a ^{235}U-enriched natural uranium fuel similar to the one used in the PWRs above
2. a fuel based on multirecycled plutonium, *i.e.*, a mixture of recycled plutonium and enriched uranium (labelled MOX-UE)
3. a fuel based on the multirecycling of plutonium, americium, neptunium and curium, mixed, as above, with enriched uranium.

3.4 Deployment scenarios considered

For each of the possible EPR fuels, two cases have been considered, namely the current handling of uranium, and uranium handling that is better optimised to spare the uranium resource.

Table 6 Characteristics of the fuel for the future EPR

	Case 1: No multirecycling	*Case 2: Plutonium multirecycling*	*Case 3: Pu + MA (Np, Am, Cm) multirecycling*
Type of fuel	UOX	MOX-UE	MOX-UE
^{235}U enriching ratio of fuel	4.9%	4.5%	4.7%
^{235}U enriching ratio of the rejected depleted uranium	0.25%	0.25%	0.25%
Pu & MA enriching ratio of fuel	0%	2.1 %	3.7%
Fuel amount loaded	13.6 tons	13.6 tons	13.6 tons
Of which Pu/Np/Am/Cm (kg)	0/0/0/0	285/0/0/0	387/17/43/60
Corresponding natural uranium	138 tons	122 tons	126.3 tons
Corresponding depleted uranium	124.4 tons	108.7 tons	113.2 tons
Uranium recovered after reprocessing	12.6 tons	12.4 tons	12.3 tons
Pu produced	170 kg	285 kg	387 kg
Pu placed in storage	170 kg	0 kg	0 kg

Note: Amounts are given per GWe.year of energy produced

Sources: de Saint Jean *et al*. (2000) and Youinou *et al*. (2003)

3.4.1 Current uranium resource handling

We find that, with light water reactors only, and with this kind of fuel handling, the target nuclear power deployment is out of reach because of the rapid depletion of the economically accessible natural uranium resource. Nuclear power generation comes rapidly to a halt for lack of fuel. This occurs sooner or later, depending on the fuel used:

- With UOX fuel in the EPRs, by 2030, the installed capacity will be twice that of today's, and the substitution of today's reactors with EPRs is achieved. Nuclear power capacity will continue to grow until 2060, reaching a maximum capacity of 2900 GWe. The natural uranium resource is drained, so that it becomes impossible to start new reactors beyond 2060; the little uranium that is still available is necessary to feed the reactors that are already running. This is shown in Figure 1 with the sudden break-off of the EPR curve. In real life, this break-off in energy generation shown in the figures should be smoother because of various factors (uranium price, discovery of new extraction potential...).
- With multirecycled plutonium on enriched uranium in EPRs, nuclear power deployment can extend to 2070, reaching a maximum capacity of 3200 GWe. The ^{235}U enriching ratio required to produce 1 GWe is reduced, thanks to the presence of another fissile element, plutonium. As a result, the draining of the natural uranium reserves is somewhat slower (see Figure 2). One should note, however, that, if Pu-based reactors were to be included in the set of reactors being considered (see below), Pu multirecycling in EPRs would be a problem, as EPRs make poor use of the Pu resource; they degrade the quality of the plutonium without consuming it entirely.

- The multirecycling of minor actinides (Np, Am, Cm) along with the Pu is less efficient for the production of energy than Pu multirecycling alone. The uranium that is mixed with the Pu and minor actinides has to have a higher enriching ratio because of the presence of neutron-consuming elements. The natural uranium resources are drained faster than in the preceding situation: nuclear power capacity stops growing in 2065, reaching a low maximum of 3100 GWe. As a result, this fuel is not given further consideration in our scenarios.

Figure 1 Nuclear power deployment with light water reactors only and for three fuels in EPRs with fuel handling as it is today

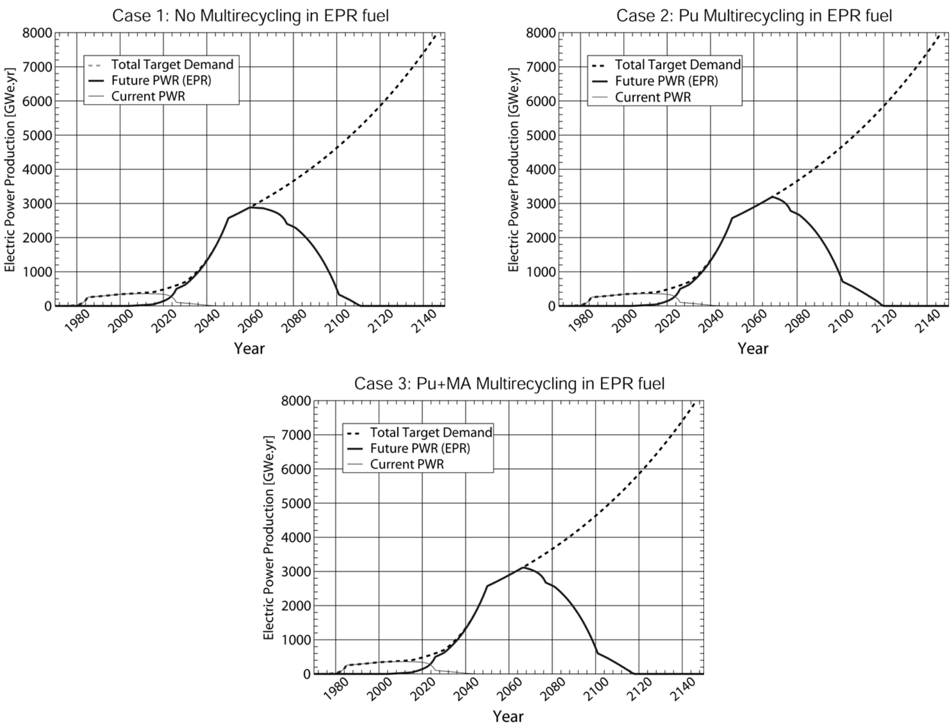
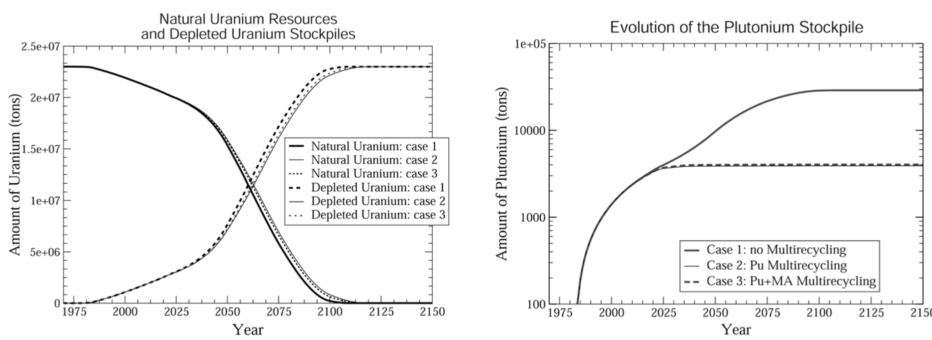


Figure 2 Natural uranium and plutonium stockpiles with light water reactors only and for three fuels in EPRs with fuel handling as it is today



3.4.2 Fuel handling optimised to spare uranium reserves

Today, the fuel cycle is open; the spent fuel is not recycled. It is stored as is, pending possible recycling decisions. Some countries, such as France, have opted for fuel recycling: the plutonium and the uranium in the spent fuel are separated. A fraction of the plutonium is recycled in MOX fuel. The reprocessed uranium is put in storage for the time being, in the event of future valorisation. It would be possible to re-enrich the reprocessed uranium and use it as fuel. It would also be possible to reduce to 0.1% the ^{235}U content of the depleted uranium from the enriching process. These options could become economically worthwhile if the costs of fossil fuels and of natural uranium were to increase.

The results for the corresponding nuclear deployment scenario and the stocks of plutonium and of natural uranium are shown in Figures 3 and 4:

- with UOX fuel in the EPRs (Case 1), nuclear power generation can continue to grow until 2065, reaching a maximum capacity of 3100 GWe
- with multirecycled plutonium on enriched uranium (Case 2), nuclear power deployment using EPRs can extend to 2085, reaching a maximum capacity of 3900 GWe, *i.e.*, 15 years longer than in the preceding subsection, with the same fuel and no fuel handling optimisation.

Figure 3 Nuclear power deployment with light water reactors only and for two fuels in EPRs, with fuel handling optimised to spare uranium reserves: EPR without multirecycling (Case 1) and EPR with Pu multirecycling (Case 2)

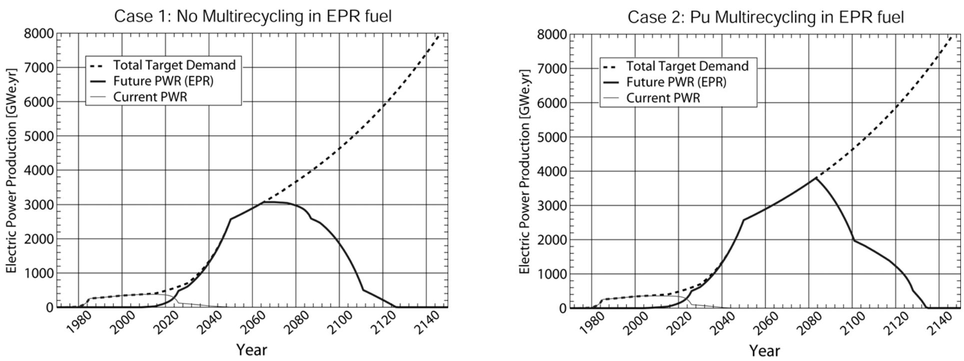
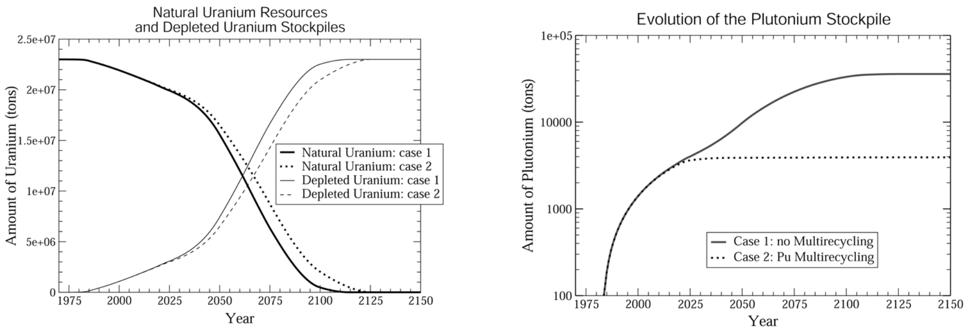


Figure 4 Natural uranium and plutonium stockpiles with light water reactors only and for two fuels in EPRs, with fuel handling optimised to spare uranium reserves: EPR without multirecycling (Case 1) and EPR with Pu multirecycling (Case 2)



This last option is the best one if only light water reactors are considered. However, it is unable to satisfy our target nuclear power demand beyond 2085 because natural uranium reserves run out. That makes this option incompatible with sustainable development, especially since other technologies able to produce sufficient energy (such as fusion) are still in the research labs.

The best solution with only light water reactors, then, would be plutonium multiple recycling. Besides the fact that such multiple recycling would be a very complex and expensive operation, it would bring nuclear power to a quasi-final end. Indeed, the only natural fissile resource (^{235}U) would be entirely consumed by about 2100 and the leftover multirecycled plutonium would be degraded: it would contain too many elements that do not undergo fission easily, so that it could not be used on its own as a reactor fuel.

Other solutions, able to extract close to 100% of the potential energy content of the raw material, thanks to breeding, have to be considered. If the sustainable development of nuclear power is to be achieved, we must resort in the short term, *i.e.*, within the next 10 to 15 years, to reactor types other than light water reactors, to reactors capable of breeding at least as much fissile matter as they consume (iso-breeders). In the following sections, we will consider fast-neutron reactors based on the U-Pu fuel cycle (Sections 4 and 6) and thermal neutron reactors based on the Th-^{233}U fuel cycle (Sections 5 and 6).

4 Scenario with light water and fast neutron reactors

4.1 Characteristics of the fast neutron reactors (FNRs) considered

Of the six systems selected by the Generation IV International Forum, four operate with a fast-neutron spectrum. Two of these fast-neutron reactors, the ones the French Atomic Energy Commission (CEA) is working on, are included in the simulation described in this section: the liquid-metal-cooled fast reactor (SuperPhoenix type) and the gas-cooled fast reactor. The characteristics of these two reactors are given in Table 7: in this simulation, both have a breeding ratio larger than one. Their fuel is depleted uranium and plutonium. Fuel loading and unloading is done every five years in the liquid metal reactor and every 15 years in the gas-cooled reactor.[2] Plutonium breeding causes depleted uranium to be consumed in the reactor. The quantity of depleted uranium that has to be input depends on the temperature in the reactor, hence on its thermodynamic efficiency. We set the thermodynamic efficiency at 40% for all the FNRs in our simulations.

We have also considered a third type of fast-neutron breeder reactor. It is started up with ^{235}U as its fissile element, and breeds the same amounts of plutonium as the liquid-metal-cooled reactor described above.

The advantage of this third type of reactor is that, since it does not need plutonium for its initial load, there is no need to start a light water reactor to produce plutonium for it. Moreover, ^{235}U is used more efficiently in an FNR than in a light water reactor: a total of 15 tonnes of ^{235}U are required to start an FNR, while a light water reactor consumes 45 tonnes of ^{235}U to produce the plutonium needed to start a liquid-metal-cooled fast-neutron reactor (two 6-tonne loads).

The characteristics of the fast-neutron reactor started up with ^{235}U are given in Table 8.

Table 7 Characteristics of the fast neutron breeder reactors considered

	Liquid metal coolant	*Gas coolant*
Output capacity	1.0 GWe	0.3 GWe
First operating date	2025	2025
Reactor lifespan	50 yrs	60 yrs
Fuel amount (per load)		
Depleted uranium	48 tons	51 tons
Plutonium	6 tons	7 tons
Reprocessing time	5 yrs	5 yrs
Loading periodicity	5 yrs	15 yrs
Number of loads	2	2
Breeding (per reactor-year)		
Depleted uranium input	1 ton	300 kg
Plutonium output	300 kg	100 kg

Table 8 Characteristics of the fast neutron breeder reactors started with ^{235}U-based fuel

	FNR started with ^{235}U *(liquid metal coolant)*
Output capacity	1.0 GWe
First operating date	2025
Reactor lifespan	50 yrs
Fuel amount (per load)	
Enriched uranium	50 tons
^{235}U enriching ratio	15%
Reprocessing time	5 yrs
Loading periodicity	5 yrs
Number of loads	2
Breeding (per reactor-year)	
Depleted U input	1 ton
Pu output	300 kg
Final discharge from reactor	
Pu amount per load	6 tons

The corresponding deployment scenarios are detailed below, in Subsections 4.3 to 4.5.

4.2 Characteristics of the light water reactors involved

Table 7 shows that the fissile matter needed for the initial inventory of a 1 GWe U-Pu-based fast-neutron breeder reactor is about equal to the amount of plutonium produced by a standard PWR-type light water reactor during its entire lifespan. In order to deploy FNR-type reactors, then, the Pu produced in the EPRs must not be recycled, large amounts of plutonium being necessary for FNR deployment.

The light water reactors involved in this deployment scenario are the existing PWRs (characteristics given in Section 3) and the future EPRs described above, with enriched natural uranium fuel (Case 1 in Table 6).

4.3 Scenario with liquid-metal-cooled FNRs

The results in terms of installed capacity and uranium and plutonium stockpiles for the nuclear-power-deployment simulation based on a combination of light water reactors and liquid-metal-cooled fast-neutron breeder reactors are shown in Figures 5 and 6.

Figure 5 Nuclear power deployment with light water reactors and liquid-metal-cooled FNRs

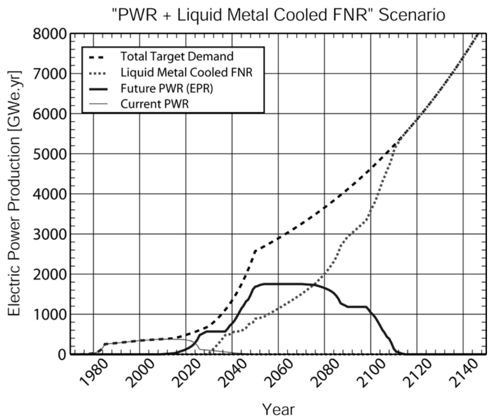
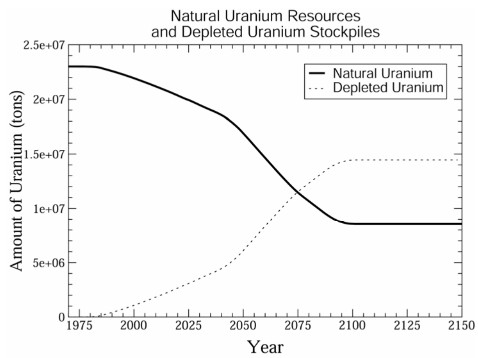


Figure 6 Uranium and plutonium stockpiles corresponding to the deployment of nuclear power with light water reactors and liquid-metal-cooled FNRs



In this scenario, in order to produce, in light water reactors, the plutonium needed for the initial inventory of the FNRs, today's installed PWR capacity has to be multiplied fivefold. These light water reactors produce enough plutonium to give the FNRs their initial impulse. Subsequently, breeding in the FNRs provides enough plutonium to continue their growth. They become predominant by 2075, and the number of EPRs in operation starts to decrease.

In this scenario we see that (Merle-Lucotte *et al*., 2004):

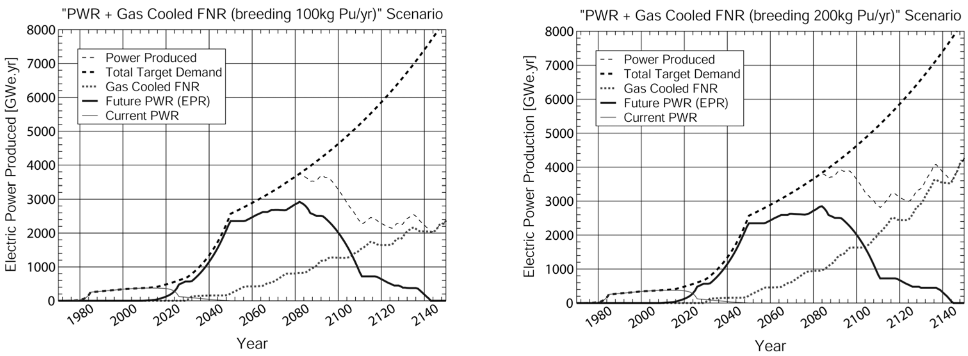
- Up to 1500 EPRs have to be started, consuming 15 million tonnes of natural uranium by 2100, leaving 35% of the natural uranium resource still available for future use.
- Large amounts of plutonium are involved: 30 000 tonnes of plutonium in the FNR fuel in 2100, and an equal amount in the reprocessing units. That is a lot of fissile matter!

In sum, this deployment scenario requires complex handling of the fuel and of the minor actinides generated. Moreover, this scenario would not be able to satisfy a significantly larger nuclear power demand (Subsection 2.1) and that possibility cannot be simply brushed off.

4.4 Scenario with gas-cooled FNRs

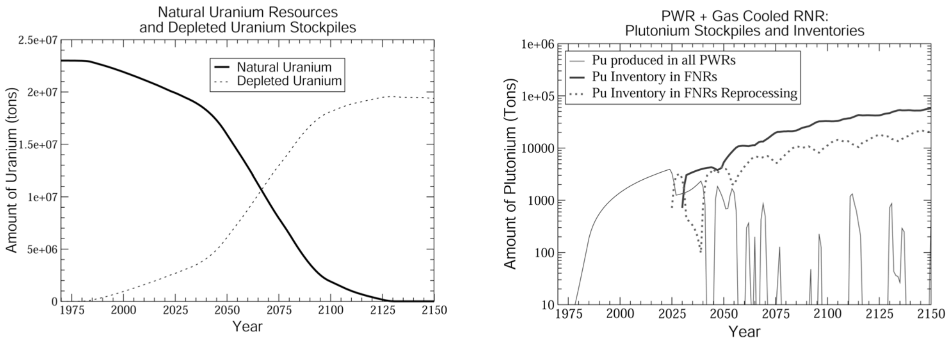
The results in terms of installed capacity and uranium and plutonium stockpiles for the nuclear-power-deployment simulation, based on a combination of light water reactors and gas-cooled fast-neutron breeder reactors, are shown in Figures 7 (left) and 8.

Figure 7 Nuclear power deployment with light water reactors and gas-cooled FNRs



In this scenario, the light water reactors are not able to produce enough plutonium to start the FNRs. EPRs have to continue to run and produce plutonium until, eventually, the natural uranium resource runs out and no new EPR can be started, the remaining uranium already being allocated. The target world energy demand cannot be met starting in 2080. Even if the plutonium breeding ratio in these gas-cooled FNRs is doubled (Figure 7, right), an unlikely event since it reaches the theoretical limit of plutonium production without taking neutron losses in the reactor into account, natural fissile uranium starts to run out by 2085. A scenario based on gas-cooled FNRs, then, does not satisfy sustainable development criteria in that it leads to a rapid depletion of natural fissile uranium reserves.

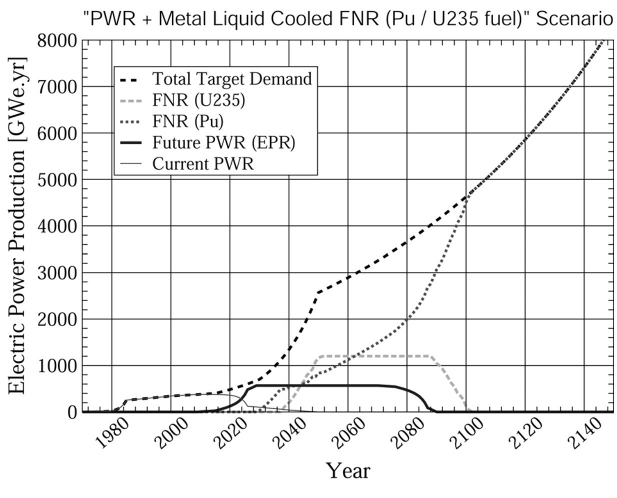
Figure 8 Uranium and plutonium stockpiles corresponding to the deployment of nuclear power with light water reactors and gas-cooled FNRs



4.5 *Scenario with liquid-metal-cooled FNRs started either with plutonium or with ^{235}U*

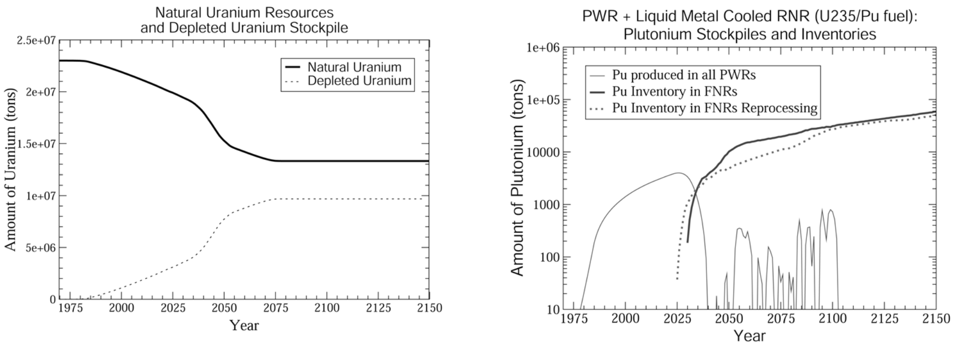
In this scenario, the FNRs started with plutonium are given highest priority, so as to help consume the plutonium stockpiles. If there is not enough plutonium to start an FNR, however, the second priority reactor is an FNR started with ^{235}U instead of, as in the first scenario discussed in Subsection 4.3, an EPR to produce the missing plutonium. The results in terms of installed capacity and uranium and plutonium stockpiles for the nuclear-power-deployment simulation, based on a combination of light water reactors and liquid-metal-cooled fast-neutron breeder reactors started either with plutonium or ^{235}U, are shown in Figures 9 and 10.

Figure 9 Nuclear power deployment with light water reactors and liquid-metal-cooled FNRs started either with Pu or with ^{235}U



The results of this scenario are similar to those of Subsection 4.3, with one difference: enough plutonium is produced with an installed capacity of FNRs started with ^{235}U that is only three times as large as the current PWR capacity. As a result, the pressure on the natural uranium resource is less intense and 55% of the reserve remains available after 2100. Moreover, the current PWRs are replaced by a quasi-equal number of EPRs, which makes the transition towards the FNRs.

Figure 10 Uranium and plutonium stockpiles corresponding to the deployment of nuclear power with light water reactors and liquid-metal-cooled FNRs started either with plutonium or with ^{235}U



Such a deployment scenario could prove useful for countries which do not have plutonium stocks, *e.g.*, countries which do not have any, or have too few, light water reactors.

However, a fleet of FNRs started with ^{235}U would require a large-scale uranium-enriching industry capable of producing enriched uranium with 15% fissile matter content.

Moreover, the same amount of plutonium in the fuel cycle and of actinides in the inventories is found in this scenario, implying the same complex handling. In addition, in the event of a decision to ban nuclear power, *e.g.*, because it is replaced by another source of energy (such as fusion), the problem arises of how to incinerate these large quantities of plutonium (a total of 60 000 tonnes in 2100) in reactors and in fuel-processing plants. A 1 GWe reactor modified to operate as a burner consumes only about 1 tonne of plutonium per year. Thus, plutonium incineration would require 60 000 reactor-years, to be compared to the 120 000 reactor-years of FNRs being operated in 2100 in this scenario. The incineration of the plutonium stocks produced in this instance appears extremely difficult. It would be an expensive and drawn-out process, near to impossible!

5 Scenario with light water and molten salt reactors

Thorium 232 capture cross-sections and ^{233}U capture and fission cross-sections are such that breeding can be achieved with a thermal neutron spectrum as well as with a fast-neutron spectrum. Breeding with a thermal neutron spectrum requires smaller quantities of fissile material, hence our choice, in this study, of the molten salt reactor based on the ^{232}Th (fertile)-^{233}U (fissile) fuel cycle in a thermal neutron spectrum. These molten salt reactors or MSRs are one of the six reactor types selected by the Generation IV International Forum.

5.1 Characteristics of the molten salt reactor involved

Any scenario that involves reactors based on the Th-^{233}U fuel cycle requires that ^{233}U be somehow produced, since this fissile element is not to be found in nature, nor is it produced in today's reactors. The option of starting MSRs with an initial load containing another fissile element, such as plutonium or ^{235}U, is not satisfactory (Nuttin *et al*., 2005) for the following reasons:

- Starting with plutonium generates excessive amounts of minor actinides, in particular ^{244}Cm.
- Starting with ^{235}U has the same drawback as starting with plutonium if the ^{235}U is mixed with ^{238}U. Moreover, ^{236}U poisoning impairs normal reactor operation for at least 50 years.

The 'conversion' of plutonium or ^{235}U into ^{233}U, then, has to be given serious consideration. It can be achieved by irradiating thorium in standard reactors: some of the neutrons emitted by the fissions in the reactor will be captured in thorium, eventually yielding ^{233}U after decay. Uranium 233 can thus be produced by breeding in thorium blankets placed either in EPRs (next section) or in FNRs, or in both reactor types (Section 6). Little information is available today on the production of ^{233}U in EPRs or FNRs, but work on this subject is in progress at the 'Groupe de Physique des Réacteurs' (Reactor Physics Group) at the Laboratory for Subatomic Physics and Cosmology (LPSC) in Grenoble, as well as at the 'Groupe de Physique de l'Aval du Cycle et de la Spallation' at Nuclear Physics Institute of Orsay (IPNO) in Orsay.

The molten salt reactor type considered in these simulations is called the 'Thorium Molten Salt Reactor' or TMSR. This concept is detailed in Merle-Lucotte *et al*. (2004), Mathieu *et al*. (2005) and Mathieu (2005). TMSRs are either iso-breeders or breeders (with a breeding ratio larger than one). In order to improve the reactor's breeding capability, a radial thorium blanket is added to the core. Escaping neutrons can produce ^{233}U in the blanket.

The characteristics of the TMSR are summarised in Table 9. The fuel is loaded once, when the reactor is first started, and thorium is added on a regular basis to ensure iso-breeding. Half the thorium load is in the reactor core, the other half being in the fuel-reprocessing unit associated with the reactor.

Table 9 Characteristics of the MSRs involved, *i.e.*, TMSRs

	TMSR
Output capacity	1.0 GWe
First operating date	2030
Reactor lifespan	50 yrs
Fuel amount (per load)	
Thorium	58 tons
Fissile matter (^{233}U) in the fuel	3%/1.7 tons
Thorium input	1 ton
^{233}U produced	1 ton
Plutonium produced	4 kg
Thorium blanket: thorium amount	21 tons

Note: The amounts are given per GWe.year of energy produced

5.2 Characteristics of the light water reactors involved

The transition light water reactors used in this scenario are today's PWRs and the future EPRs, whose fuel is enriched uranium with plutonium multirecycling, as in Case 2 of Table 6. Now, however, they are producing ^{233}U instead of plutonium, thorium MOX being added in the core. The reason the multirecycling option is chosen for the EPRs is that, in this scenario, there is no other reactor able to consume the Pu so that it is the best way to avoid large accumulations of this material. It is assumed that the minor actinides are incinerated in other, future, reactor types such as Accelerator Driven Systems (ADS) or Generation IV burners.

The characteristics of the ^{233}U-producing EPRs are given in Table 10.

Table 10 Characteristics of future EPRs used to produce ^{233}U

	Thorium MOX fuel
Output capacity	1.45 GWe
First operating date	2010
Reactor lifespan	50 yrs
^{235}U enriching ratio for the fuel	4.5%
^{235}U enriching ratio of the rejected depleted uranium	0.25%
Fuel amount	13.6 tons
Spent fuel to be reprocessed	12.4 tons
^{233}U production	
Thorium input	133 kg
^{233}U produced	133 kg

Note: Amounts are given per GWe.year of energy generated

5.3 Deployment result with light water reactors and molten salt reactors

As shown in Figure 11 (left), this scenario is able to meet the target energy demand, but more than half of the natural uranium reserves are used up (Figure 12). This is because continuous operation of a large number of light water reactors is necessary to produce the ^{233}U needed to start the TMSRs. This problem can be solved if, starting in 2050, the TMSRs are considered capable of breeding approximately 10 kg of ^{233}U per year. The 20-year delay between the first TMSRs and the TMSRs with a higher breeding ratio corresponds to the time needed to develop an optimised TMSR technology. The results obtained with this option are shown in Figure 11 (right). As Figure 12 shows, only one-third of the natural uranium reserves are consumed. Sensitivity tests have shown that a slight variation in the production of ^{233}U in the light water reactors or a small variation in the ^{233}U inventory in the TMSRs does not modify the results of this scenario in any significant way.

A problem remains: the stocks of plutonium produced in the light water reactors, even if they are twenty times less abundant than in the previous scenario (Subsection 4.5), will have to be incinerated. A possibility is the one examined in the next section, a solution that also includes fast-neutron reactors. These can make efficient use of the plutonium and thus close the fuel cycle.

Figure 11 Nuclear-power deployment – scenario with light water reactors and MSRs that are iso-breeders (left) and iso-breeders becoming breeders (right)

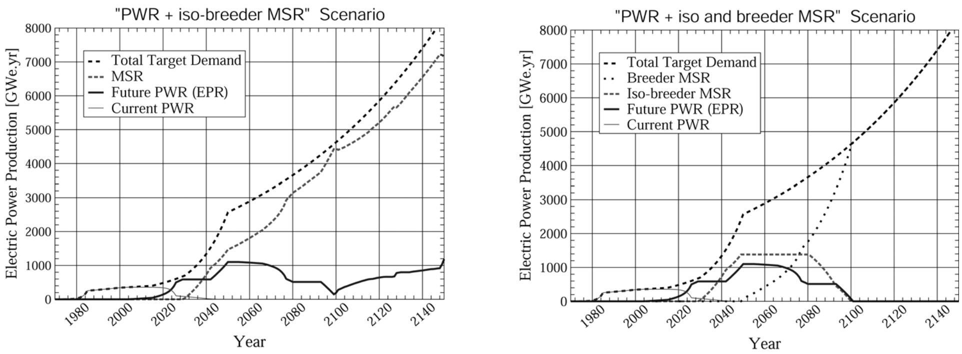
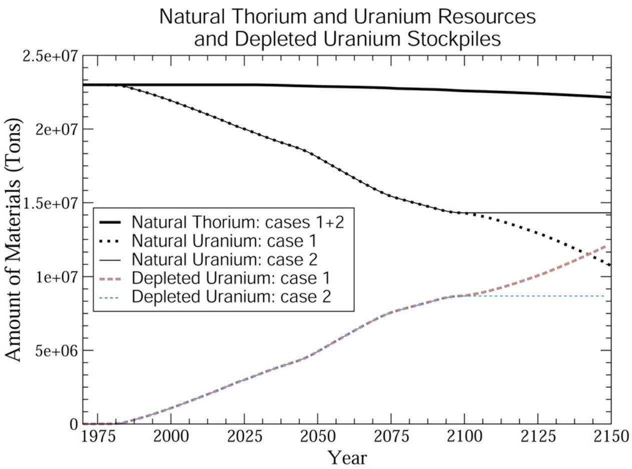


Figure 12 Natural uranium and thorium stocks, and depleted uranium stockpile in nuclear power deployment with light water reactors and MSRs that are iso-breeders (Case 1) and iso-breeders becoming breeders (Case 2)



6 Scenario with light water reactors, FNRs and TMSRs

This optimised scenario calls on the three types of reactors described in the previous sections, so as to make an efficient transition from today's reactors towards a sustainable reactor technology that implies breeding. In this scenario the ^{233}U that is needed in the molten salt reactors is bred in solid thorium blankets in the EPRs and in the FNRs that are deployed.

6.1 Characteristics of the light water reactors involved

The transition light water reactors in this scenario are today's PWRs and the future EPR-type reactors using an enriched uranium fuel with no plutonium or minor actinide recycling (Case 1 in Table 6); however, in this instance, they produce some ^{233}U. For this purpose, a thorium blanket is added to the core. The reason the plutonium and minor actinide multirecycling option is not chosen for this scenario is that the plutonium and minor actinides can be consumed more efficiently in the FNRs.

The characteristics of these ^{233}U-producing EPRs are given in Table 11.

Table 11 Characteristics of the future ^{233}U-producing EPRs

	UOX fuel
Output capacity	1.45 Gwe
First operating date	2010
Reactor lifespan	50 yrs
^{235}U enriching ratio for the fuel	4.9%
^{235}U enriching ratio of the rejected depleted uranium	0.25%
Fuel amount	13.6 tons
Spent fuel to be reprocessed	12.6 tons
Plutonium produced to be reprocessed	130 kg
^{233}U production	
Thorium input	130 kg
^{233}U produced	130 kg

Note: Amounts of material are given per GWe.year of energy generated

6.2 *Fast neutron reactors involved*

Only one of the fast-neutron reactor types described in Section 4 has been considered here: the liquid-metal-cooled reactor whose characteristics are better known. The FNRs here, consume plutonium to breed ^{233}U, the result being that plutonium stocks are reduced and the ^{233}U needed to start the MSRs is produced.

The characteristics of these FNRs are given in Table 12.

Table 12 Characteristics of the ^{233}U-breeding fast neutron reactors involved in this scenario

	Liquid metal coolant
Output capacity	1.0 GWe
First operating date	2025
Reactor lifespan	50 yrs
Fuel amount (per load)	
Depleted uranium	48 tons
Fissile matter (Pu) in fuel	11%/6 tons
Reprocessing time	5 yrs
Loading periodicity	5 yrs
Number of loads	2
Depleted uranium input per year	1 ton
Pu input per year	200 kg
Th input per year	500 kg
^{233}U production per year	500 kg

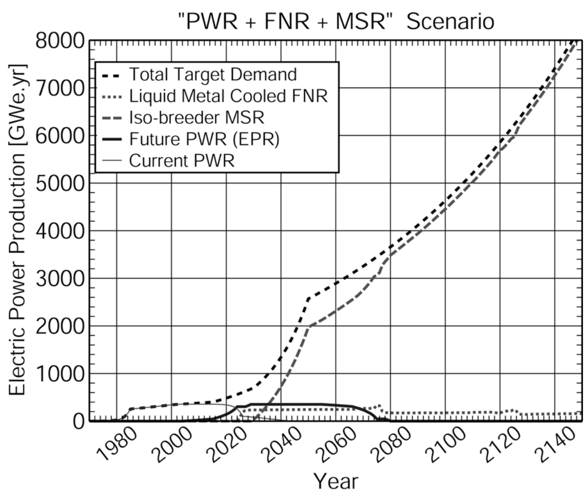
6.3 Molten salt reactors involved: TMSR

The MSRs considered here are TMSRs, whose characteristics are discussed in the preceding section and summarised in Table 9. The ^{233}U needed to start the TMSRs is produced both in the EPRs and in the FNRs in this scenario. As FNRs continue to operate during the entire duration of the scenario, sufficient amounts of ^{233}U are constantly available and breeding is not necessary in the TMSRs. As a consequence, iso-breeding TMSRs are used in this scenario.

6.4 Deployment results including light water reactors, liquid-metal-cooled FNRs and TMSRs

With this scenario, as shown in Figure 13, today's reactors are fully replaced by 2030 with EPR-type light water reactors. The EPRs are progressively replaced with FNRs and TMSRs, and they are shut down in 2080 or so. The transition towards sustainable Generation IV reactors is then complete.

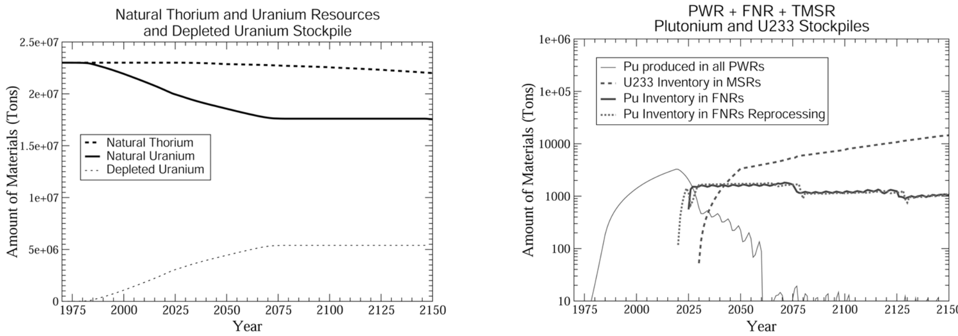
Figure 13 Nuclear power deployment with light water reactors, liquid-metal-cooled FNRs and TMSRs



The ^{233}U needed to start the TMSR reactors can be produced by the same number of light water reactors that we have today, plus an equivalent number of FNRs. Molten salt reactors are dominant by 2035 and their breeding capability makes for successful development of nuclear power beyond that date.

As for the plutonium produced, it is in the inventory of the FNRs; Figure 14 (right) shows that the maximum amount built up is ten times less than in the deployment scenario with only light water reactors and liquid-metal-cooled FNRs. In order to make sure the plutonium produced in the light water reactors is consumed, we have chosen to set the highest priority on FNR-type reactors as long as enough plutonium is available. Figure 14 (right) shows that the plutonium accumulated before the first FNRs are started is divided by two in 2100. In this scenario, the U-Pu fuel cycle is closed, thanks to the FNRs.

Figure 14 Natural uranium and thorium reserves, plutonium and ^{233}U stockpiles corresponding to the deployment of nuclear power with light water reactors, liquid-metal-cooled FNRs and TMSRs



The target nuclear power demand is met during the entire duration of the scenario (Figure 13), and this is achieved without draining the natural uranium and thorium reserves (Figure 14, left). Only one-third of the natural uranium and a tiny fraction of the thorium reserves are consumed during the entire time period considered for the deployment. As a consequence, a larger demand could be met without difficulty.

We find, then, that this scenario based on the three reactor types considered in our simulations is, by far, the most efficient. It offers faster and more flexible deployment than any of the other scenarios, and also faster and more flexible shutdown, if needed. Indeed, TMSRs operate with little fissile matter. A TMSR, if it is modified to operate as an incinerator, can burn up to 1 tonne of ^{233}U per year, *i.e.*, practically a full load of fissile matter. This could allow a nuclear power shutdown without leaving behind fissile matter stockpiles such as those of the scenario discussed in Section 4.5.

We note also that the amounts of plutonium and minor actinides produced are significantly (several orders of magnitude) smaller than in the other scenarios. This makes waste management and, as a result, the whole deployment process, simpler and easier to implement.

Finally, in the event that all the reactors would be shut down and the residual fissile matter fully incinerated, if the need to start nuclear power again were to arise, there would still be enough natural uranium to do so.

This scenario brings to light the importance of the Th-^{233}U fuel cycle in general and, more specifically, that of the molten salt reactor concept: efficient and sustainable nuclear power deployment is achievable, in conjunction with optimised fissile matter use and waste production.

A palette of intermediate scenarios can be considered, ranging from the option with only light water reactors and FNRs of Section 4 to the option in this section, with the three types of reactors and predominance for molten salt reactors. Such intermediate scenarios would change the number of FNRs, with a resulting buildup of plutonium stockpiles lying between those of Figure 10 and Figure 14.

7 Conclusions and prospects

This study is based on an eightfold increase in nuclear power in 2050 from today's nuclear power capacity, which may be a low figure. We examined the means already available, or that should be developed, in order to meet this demand in a sustainable way.

With nuclear power production continued with the same means used today, *i.e.*, with light water reactors, even with the most favourable scenario, *i.e.*, with plutonium multirecycling and optimised handling of ^{235}U, the target worldwide nuclear power demand cannot be met beyond 2085 for lack of natural uranium, the reserves having been drained by then. This, of course, is incompatible with the notion of sustainable development in the present context, where alternative energy production technologies (such as fusion) are still in the research labs. Moreover, such multirecycling would be complex and expensive, and it would, in addition, damage the plutonium, the only fissile material available once the natural resources have completely run out. Restarting nuclear power production in any significant way would then be very expensive.

The second option we explored is a combination of light water reactors and FNRs. The best scenario in this category is able to meet the target worldwide nuclear power capacity during the entire time interval considered. However, it leads to the accumulation of large amounts of plutonium and minor actinides residing in the reactors and the fuel-reprocessing units, implying complex handling procedures. Moreover, in the event that nuclear power generation is stopped, *e.g.*, because it can be replaced by another source of energy (such as fusion), the incineration of the plutonium stockpiles will be a problem, this incineration being difficult, expensive, drawn out, near to impossible. Restarting nuclear power production after having stopped it would again prove very expensive.

The third option considered in this study is a combination of light water reactors and molten salt reactors based on the ^{232}Th-^{233}U fuel cycle. In this case also, the target worldwide nuclear power capacity can be met over the full duration, but significant stockpiles of deteriorated plutonium are accumulated with no incineration possibilities, so that the fuel cycle of the light water reactors is not closed.

Finally, the last option examined consists in a combination of the three reactor types considered in the course of this study: light water reactors, FNRs and MSRs. This appears to be, by far, the most efficient scenario. It allows the fastest and most flexible deployment, as well as the fastest and most flexible stopping of nuclear power if such a decision were to be made. The role of the FNRs is also to close the U-Pu fuel cycle, and the amounts of plutonium and minor actinides produced are significantly smaller than in the preceding options. As a result, waste management is made simpler and easier to implement. Nuclear power deployment in this case is sustainable and efficient, and the use of fissile matter and the production of wastes are optimised.

We would like to stress here that some of the data used for these simulations, in particular plutonium breeding ratios and the production of ^{233}U in EPRs and FNRs, come from estimations. Better-founded data will be obtained, thanks to a CNRS research programme that is in progress at the 'Groupe de Physique des Réacteurs' at LPSC in Grenoble and at the IPN in Orsay. Preliminary tests have established that the conclusions reached here are not very sensitive to the hypotheses formed on these system characteristics.

This study will be continued in order to include, in particular, some local aspects of the deployment. On one hand, difficulties may appear, *e.g.*, the need to exchange or transport fissile and/or radiotoxic materials between regions, or risks of proliferation. On the other hand, all countries are 'not equal' *vis à vis* nuclear power. It would be interesting to study the future deployment of nuclear power in two distinct types of regions, *i.e.*:

1 In a region like Europe, which already has a number of light water reactors and, as a consequence, fair amounts of plutonium, in which the growth of nuclear power will be moderate in the next 100 years. A scenario based on a combination of light water reactors and FNRs is valid here, if other regions resort to the Th-^{233}U fuel cycle.

2 In an area like Southeast Asia, whose energy demand and, as a consequence, whose demand on nuclear power, will grow rapidly in the coming years. Here, a scenario based solely on light water reactors would be unrealistic, as would be a scenario based on a combination of light water reactors and FNRs, which would require large amounts of plutonium. Here, an option including molten salt reactors would be much more flexible and would allow faster growth. It would be particularly well adapted to the area.

The global scenarios presented in this paper illustrate the limitations that worldwide nuclear power deployment suffers, while demonstrating how complementary the different reactor types are. This study brings to light the strongly constraining fact that sufficient amounts of fissile matter must be available if breeder reactors are to be started. Besides, these breeder reactors will not be industrially available before 20 to 25 years from now. In order to ensure the growth of nuclear power and its transition towards a sustainable reactor fleet, then, it is necessary to build second- and third-generation reactors.

Our study shows that a global and balanced solution is available, which reconciles fuel-cycle closing, nondepletion of the natural resource, reduced production of long-lived wastes and the possibility of stopping/restarting nuclear power generation rapidly. It rests on a combination of light water reactors and breeder reactors, which are necessary to burn the plutonium and produce ^{233}U, and on the Th-^{233}U fuel cycle, which we feel cannot be circumvented.

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References

Bauquis, R.P. (1999) 'Un point de vue sur les besoins et les approvisionnements en énergie à l'horizon 2050', *La revue de l'Energie*, Septembre, No. 509, (in french).

Criqui, P. (2004) *Modèle POLES du LEPII-EPE: résultats préliminaires à l'horizon 2050*, Laboratoire d'Economie de la Production et de l'Intégration Internationale (LEPII), département Energie et Politiques de l'Environnement (EPE), Grenoble, France, private comunication.

de Saint Jean, C., Delpech, M., Tommasi, J., Youinou, G. and Bourdot, P. (2000) 'Scénarios CNE: réacteurs classiques, caractérisation à l'équilibre', *rapport CEA DER/SPRC/LEDC/99-448* (in French).

ELECNUC, CEA (2003) *Les Centrales Nucléaires dans le Monde* (in French).

Heuer D. and Merle-Lucotte, E. (2004) *Programmes de simulation du déploiement de l'électro-nucléaire dans l'environnement DALI: module Scénarios Du Futur*, internal note http://lpsc.in2p3.fr/gpr/french/gpr.html (in french).

International Atomic Energy Agency (IAEA) (2002) *Uranium 2001: Resources, Production and Demand*, OECD Publishing.

Loiseaux, J-M., *et al*. (2004) 'L'énergie nucléaire d'ici 2050, une réflexion et des recommandations d'un groupe de scientifiques du CNRS dans le cadre du Programme Energie du CNRS', *Nucléaire du futur – Fission*, Groupe d'Analyse Thématique 11-a, CNRS/PACE/DIR 2004.1 (in french).

Luciani, J.F. and Simon, A. (2002) 'Les ressources d'uranium fissile permettent-elles de répondre à une forte croissance de l'énergie nucléaire mondiale?', *Rapport CEA HC/AS/em/2002-192*, Octobre (in French).

Mathieu, L. (2005) 'Cycle Thorium et Réacteurs à Sel Fondu: Exploration du champ des Paramètres et des Contraintes définissant le Thorium Molten Salt Reactor', *PhD Thesis*, Institut National Polytechnique de Grenoble, France (in French).

Mathieu, L., Heuer, D. *et al*. (2005) *The Thorium Molten Salt Reactor: Moving on from the MSBR*, submitted to Progress in Nuclear Energy.

Merle-Lucotte, E., Mathieu, L., Heuer, D., Loiseaux, J-M., *et al*. (2004) 'Molten salt reactors and possible scenarios for future nuclear power deployment', in American Nuclear Society (Ed.) *Proceedings of the Physor 2004 Conference The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments*, pp.1–12.

Nifenecker, H., Heuer, D., Loiseaux, J.M., Méplan, O. and Nuttin, A. (2003) 'Scenarios with an intensive contribution of nuclear energy to the world energy supply', *Int. J. Global Energy*, Vol. 19, No. 1, pp.63–77.

Nuttin, A., Heuer, D. *et al*. (2005) 'Potential of thorium molten salt reactors: detailed calculations and concept evolution with a view to large scale energy production', *Progress in Nuclear Energy*, Vol. 46, No.1, pp.77–79.

The Future of Nuclear Power (2003) *An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, Chap. 4, http://web.mit.edu/nuclearpower.

Youinou, G., Varaine, F. and Vasile, A. (2003) 'Plutonium and Americium multirecycling in the European Pressurized Reactor (EPR) using slightly over-moderated U-235 enriched MOX fuel assemblies', *International Conference on Advanced Nuclear Energy and Fuel Cycle Systems (Global 2003)*, New Orleans, USA.

Notes

1 EPR has been chosen as an example of a third-generation reactor. Choosing a different third-generation reactor would not change the conclusions reached for this scenario.

2 Fuel replacement periodicity depends mainly on the specific power released in the fuel elements, the specific power itself depending on the coolant.