Prospective scenarios of nuclear energy evolution over the XXIst century

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Abstract

In this paper, different world scenarios of nuclear energy development over the XXIst century are analyzed, by means of the EDF fuel cycle simulation code for nuclear scenario studies, TIRELIRE – STRATEGIE.

Three nuclear demand scenarios are considered, and the performance of different nuclear strategies in satisfying these scenarios is analyzed and discussed, focusing on natural uranium consumption and industrial requirements related to the nuclear reactors and the associated fuel cycle facilities. Both thermal-spectrum systems (Pressurized Water Reactor and High Temperature Gas-cooled Reactor) and Fast Reactors are investigated.

KEYWORDS: World nuclear scenario, nuclear energy, natural uranium, PWR, HTGR, FBR, TIRELIRE – STRATEGIE

1. Introduction

In 2005, the world nuclear installed capacity was equal to 369 GWe (440 reactors), for an electricity production of 2600 TWhe in 2004 (about 17% share). Additionally, 19 GWe were under construction, mainly in ex-USSR and Asia countries.

Many analysts forecast an increase of the nuclear energy share over the rest of this century (both for electricity and hydrogen production) because of the well-known probable reduction of electricity production by means of fossil resources, as a consequence of their increasing price due to exhaustion and the attempt to reduce greenhouse gas emissions. In this context, the natural uranium availability clearly becomes a central issue to ensure long-term sustainability to nuclear energy, but great uncertainties on the evolution of the uranium price over the next decades remain. These issues are at the origin of the debate whether the open-cycle or the closed cycle will be the predominant strategy on the world-scale.

In this paper, whose objective is to bring a modest contribution to this debate, different scenarios of nuclear energy evolution over the XXIst century are modeled and the performance of different fuel cycle strategies (based on PWR, HTGR and FBR) are inter-compared.

The results of this study, which was carried out by means of the EDF fuel cycle simulation code, TIRELIRE – STRATEGIE, will focus on natural uranium consumption and industrial requirements associated to the nuclear reactors and the associated fuel cycle facilities (mass fluxes and inventories); hence, no economical considerations will be presented in this paper.

2. TIRELIRE – STRATEGIE general features

TIRELIRE – STRATEGIE [1] is a calculation code aimed at simulating the operation of a nuclear fleet and the associated fuel cycle facilities over a long period of time (decades, even centuries). It is used to analyze the consequences of strategic choices related to the nuclear fleet composition (reactors and fuels) and other fuel cycle facilities features.

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The code calculates the power capacity to be installed every year, on the basis of the total power demand and the number of units needing replacement, because their maximum lifetime is reached. The main reactor types are currently modeled in TIRELIRE – STRATEGIE, with models based on CEA reference neutronic codes: current and advanced PWR, and HTGR – with models based on APOLLO2 calculations – FBR and ADS systems – with models based on ERANOS. Once the nuclear fleet composition is determined, the fresh and discharged fuel composition is assessed by means of fuel equivalence and evolution models (see § 2.2). Afterwards, the Spent Nuclear Fuel (SNF) cooling and reprocessing are simulated. The simulation's main results are the uranium consumption, required Separation Work Units (SWU) and mass flows for each reactor type, fuel cycle plants, interim storage and final geological repository.

2.1 FBR modeling

FBRs show the best performances in terms of Breeding Gain (BG) when fed with MOX fuel (Pu and depleted uranium). But, in the case of an insufficient Pu amount, FBR start-up can be done with highly-enriched uranium (UOX): then, when a sufficient Pu stock will be available to keep the core almost self-breeder (BG=0) or breeder, the core will be converted from UOX to MOX fuel.

In the case of MOX fuel, the Pu isotopic composition may change with time for different reasons (radioactive decay – e.g. the β^- decay of ^{241}Pu to ^{241}Am – nuclear strategy and industrial constraints, fuel cycle options, etc.).

Hence the following problems arise, at a given year *i* of a simulation:

1. Once the Pu isotopic vector at the year *i* for the fresh fuel fabrication is known, the calculation of the Pu content needed to comply with the targeted cycle length. This is usually referred to as the *equivalence calculation.*
2. Once the fresh fuel composition at the Beginning of Cycle (BOC), f_i^{BOC}, is determined, the calculation of the End of Cycle (EOC) composition, f_i^{EOC} (the *evolution calculation*).

Two methods are available to perform the equivalence and evolution calculation:

1. Direct coupling of TIRELIRE – STRATEGIE with ERANOS, a deterministic modular code system for fast reactor neutronics. For each fuel reload, ERANOS calculates both the fresh fuel Pu content corresponding to the desired reactivity value at EOC (*equivalence calculation*) and the isotopic composition of the SNF at discharge (*evolution*), with a burn-up and decay actinides chain from ^{231}Pa to ^{248}Cm. This method is highly time-consuming; therefore, it is mainly employed as a reference calculation, in order to validate the simplified method described below.
2. A semi-analytical approach based on a first-order perturbation around a specified fuel composition, considered as the reference one. This method is also based on ERANOS calculations which are executed once for all scenarios (with fixed values of both the reload batch size and the fuel burn-up) in order to calculate, for each FBR concept, a set of equivalent-^{239}Pu weights and an evolution perturbation matrix, allowing to solve the equivalence and evolution calculation, respectively. This simplified method, in spite of an accuracy which is subjected to the validity of the first-order perturbation hypothesis, shows excellent performance and a negligible calculation time. For a complete description Cf. Ref. [1, 2], in which some validation elements against ERANOS are also presented.

2.2 Thermal reactor modeling

The equivalence and evolution calculations for thermal reactors are modeled by means of the ECRIN and STRAPONTIN codes. For a complete description, Cf. Ref. [1].

3. Scenarios description

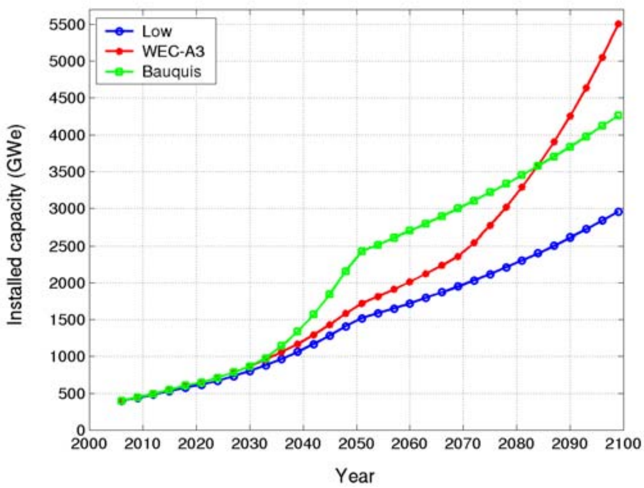
3.1 World nuclear energy scenarios

In 2005, the world nuclear installed capacity was equal to 369 GWe (440 reactors), for an electricity production of 2600 TWhe in 2004 (about 0.6 Giga-tons oil equivalent, Gtoe).

The three following scenarios of nuclear electricity demand over the XXIst century are analyzed (Cf. Figure 1):

- **Low:** the nuclear production in 2050 is 2.5 Gtoe, corresponding to an installed nuclear capacity of 1500 GWe[2] (growth rate of 3.2%/yr. between 2005 and 2050). The growth rate decreases to 1.4%/yr. between 2050 and 2100, leading to a two-fold production in 2100 (5 Gtoe, for an installed power of 3000 GWe);
- **WEC-A3:** high growth scenario [3], world population (resp. primary energy demand) of 10.1 billion (25 Gtoe) in 2050 and 11.7 billion (45 Gtoe) in 2100. The nuclear share is moderate in 2050, 11% of primary energy, 2.8 Gtoe, corresponding to an installed nuclear power of 1700 GWe (nuclear electricity growth about 3.5%/yr. in the period 2005-2050) and 21% in 2100, 9.4 Gtoe, corresponding to 5600 GWe (growth rate about 1.8%/yr. between 2050 and 2070 and 2.9%/yr. in the period 2070-2100);
- **Bauquis-based:** in a French study [4] dealing with short term (2020) and medium term (2050) energy mix, the author[3] presents a scenario in which the emphasis is not on the uncertainties of the energy demand, but on the potential limitations on the offer of fossil fuels and mainly of oil and gas. It follows a large increase of the nuclear production in 2050, 4 Gtoe, 22% of the primary energy (18 Gtoe). This scenario has been modeled up to 2050, when the installed capacity is 2400 GWe, and then extended[4] up to 2100 with a low growth rate about 1.2%/yr. between 2050 and 2100, like in the Ref. [5]. The installed capacity in 2100 is equal to 4300 GWe (7.2 Gtoe). It can be seen on Figure 1 that this scenario is the highest up to 2085, exceeded by the WEC-A3 afterwards.

Figure 1: Evolution of the nuclear electricity demand in the three considered scenarios.



3.2 Nuclear strategies

The world nuclear fleet start-up was modeled from the ’60s up to 2005. Average values for PWR were taken, enough representative of the current world fleet, in which Light Water Reactors represent 91% of the total 369 GWe installed (66% PWR and 25% BWR).

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[2] The average load factor is 82% up to 2020 and 86% afterwards (1 Gtoe = 4500 TWhe).
[3] Special Advisor to the Chairman of the Petroleum Company Total.
[4] This scenario, extending from 2000 up to 2100, will be referred to as “Bauquis” for simplicity in the rest of the paper, even if the original appraisal by Bauquis was limited to 2050.

From 2006 up to 2030, we considered that all the new reactors deployed are PWR EPR-type (European Pressurized Reactor): average discharge burn-up about 60 GWd/tHM, 4.9% enriched uranium in the fresh fuel, 60 yrs. lifetime.

Then, as early as 2030, four different strategies are considered:

1. **PWR-only:** even after 2030 and until the end of the century, new reactors commissioned are all PWR-type and identical to the EPR. Once-through PWR is the main strategy but the principal results concerning Pu monorecycling will also be presented;
2. **PWR+HTGR:** new reactors deployed after 2030 (to satisfy the increasing demand as well as for the renewal of ageing EPR) are all prismatic HTGR, with an average discharge burn-up of 120 GWd/tHM, 15% ^{235}U-enrichment, 60 yrs. lifetime;
3. **PWR+FBR MOX:** MOX-fueled FBRs are deployed as early as 2030, with a kinetics which is dependent on the Pu availability for the fresh MOX fuel fabrication. Pu is issued from PWR and FBR SNF reprocessing (loss rate of 0.1% for Pu and U and 100% for MAs). If a Pu lack appears and, thus, the FBR deployment kinetics is not sufficient to satisfy the demand, new PWRs will be deployed, but the highest priority is given to FBRs all along the century. FBRs are modeled by Na-cooled European Fast Reactor (EFR). In spite of higher values with respect to the reference EFR concept (in which the maximum BG is about 0.15), BGs of 0.2 (for the reference case) and 0.3 (increased value to evaluate the sensitivity to the BG) were considered in this study. The average discharge burn-up is 140 GWd/tHM, in-core irradiation time of 6 yrs., extra-core time of 4 yrs. (2 yrs. SNF cooling time and 2 yrs. ageing time). The FBR lifetime is equal to 60 yrs.
4. **PWR+FBR MOX/UOX:** like in the previous strategy, the highest priority is given to MOX FBR. But in the case of a Pu lack, instead of deploying new PWRs, FBRs are started-up with UOX fuel. Afterwards, when a new amount of Pu will be available for fresh MOX fuel fabrication, UOX FBRs will be converted into MOX FBRs. Thus, UOX FBR represents a transitory solution to satisfy a peak of nuclear demand with FBRs instead of deploying new PWRs.

The annual capacity of all the associated fuel cycle facilities – e.g. enrichment (UOX fuel for PWRs, HTGRs and UOX FBRs), fabrication and reprocessing for UOX and MOX fuel – is computed to satisfy the demand at any year of the scenario.

4. Uranium resources

The status of uranium resources, taken from the ‘Red book’ [6], is indicated in Table 1, as a function of the cost of recovery. In particular, the 2005 edition indicates at the level of 4.743 MtonsU the Identified Resources, 14.798 MtonsU the Conventional Resources and about 22 MtonsU the amount of Unconventional Resources associated with uranium in phosphates.

Table 1: Uranium resources (million tonsU).

<table>
<tr><td></td><td colspan="4">Conventional</td><td>Phosphates</td></tr>
<tr><td rowspan="2">Cost of recovery ($/kgU)</td><td colspan="2">Identified</td><td rowspan="2">Prognosticated</td><td rowspan="2">Speculative</td><td rowspan="7">22</td></tr>
<tr><td>RAR</td><td>Inferred</td></tr>
<tr><td>< 40</td><td>1.947</td><td>0.799</td><td rowspan="2">1.700</td><td rowspan="3">4.557</td></tr>
<tr><td>40 - 80</td><td>0.696</td><td>0.362</td></tr>
<tr><td>80 - 130</td><td>0.654</td><td>0.285</td><td>0.819</td></tr>
<tr><td>> 130</td><td>–</td><td>–</td><td>?</td><td>2.979</td></tr>
<tr><td>Total</td><td colspan="2">4.743</td><td colspan="2">10.055</td></tr>
</table>

For the current study, two different levels were considered:

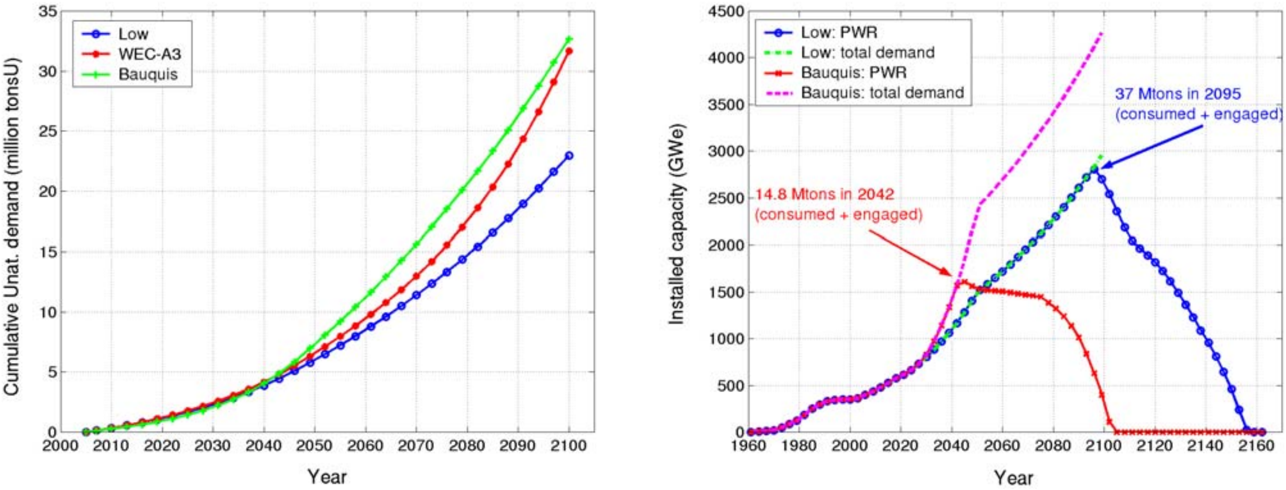
1. A lower level of 14.8 MtonsU, corresponding to *Conventional Resources* (given by the sum of Identified Resources – Reasonably Assured Resources (RAR) plus Inferred Resources – Prognosticated and Speculative Resources);
2. A higher level of 37 MtonsU, obtained by the addition of the Uranium amount in Phosphates to *Conventional Resources.*

5. Results and discussion

5.1 Once-through PWR-only

The main results are given in Figure 2. The cumulative natural U demand (computed as from 2005) exceeds the amount of the *Conventional Resources* (14.8 MtonsU) between 2070 and 2080. But, if the U amount engaged to feed the PWRs installed at a given year during all their lifetime (hence, the U *still to consume*) is added to the cumulative demand (hence, to the U *already consumed*) at a given year, the result shown Figure 2b indicates that the U shortage would occur between 2042 – Bauquis scenario with 14.8 MtonsU consumed + engaged – and 2095 – Low scenario in the case of 37 MtonsU. After the date at which all the resources are engaged, the PWR installed power decreases with a profile which is function of their age, as no new PWR could be deployed because of the U shortage.

Figure 2: a) Cumulative natural uranium demand in the once-through PWR-only strategy.
b) PWR installed capacity as a function of the scenario and of uranium resources.

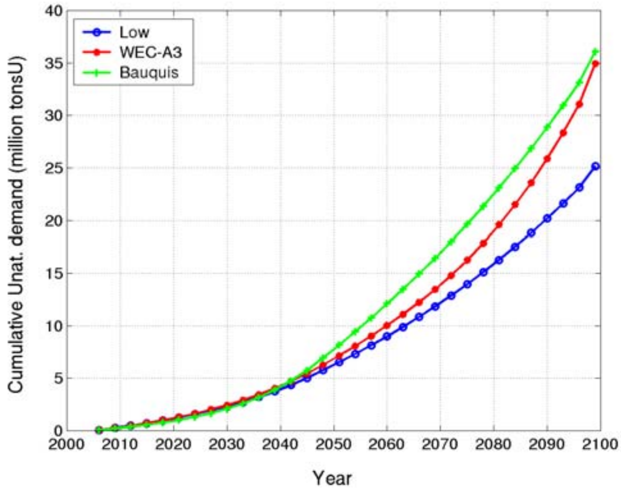


In case of Pu monorecycling in PWR, the results are very close: the date at which the total *Conventional* (14.8 MtonsU) or *Conventional + Phosphates* (37 MtonsU) resources are engaged is shifted by 3-4 yrs., allowing a supplementary installed capacity of about 200 GWe obtained by means of the MOX fuel.

5.2 Once-through PWR+HTGR

HTGRs show a higher natural U consumption than PWRs (the natural U consumption of the HTGR simulated in this study is about 15% higher than for a PWR EPR-type), Cf. Figure 3. The date at which the demand exceeds the amount of *Conventional Resources* occurs a few years before. Alternative fuel cycles based on the Th-Pu cycle are currently being investigated [7], in order to reach sustainability while answering to industrial high temperature demand and keeping the intrinsic safety characteristic of the HTGR concept.

Figure 3: Cumulative natural uranium demand in the once-through **PWR+HTGR** strategy.



5.3. Na-cooled FBR

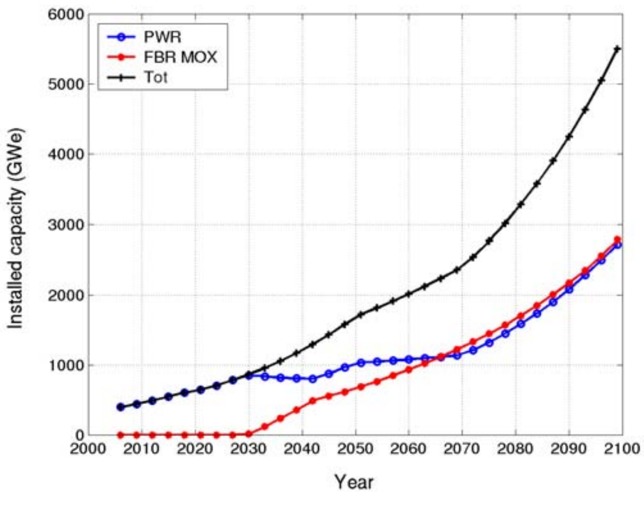
First, the WEC-A3 scenario is presented, and then it will be compared with the two others demand scenarios.

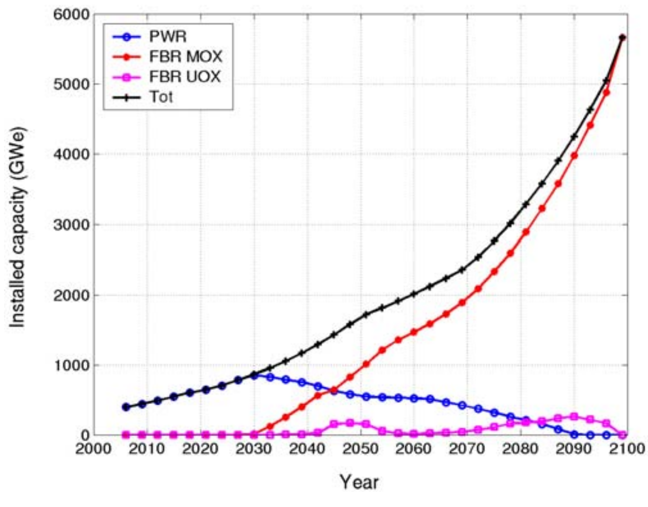
5.3.1. WEC-A3 scenario

Reference case (BG = 0.2, FBRs deployment as early as 2030)

The deployment of MOX FBR (**PWR+FBR MOX** strategy) in the WEC-A3 scenario leads to the results of Figure 4a.

Figure 4: WEC-A3 scenario: (a) **PWR+FBR MOX** strategy.
(b) **PWR+FBR MOX/UOX** strategy.



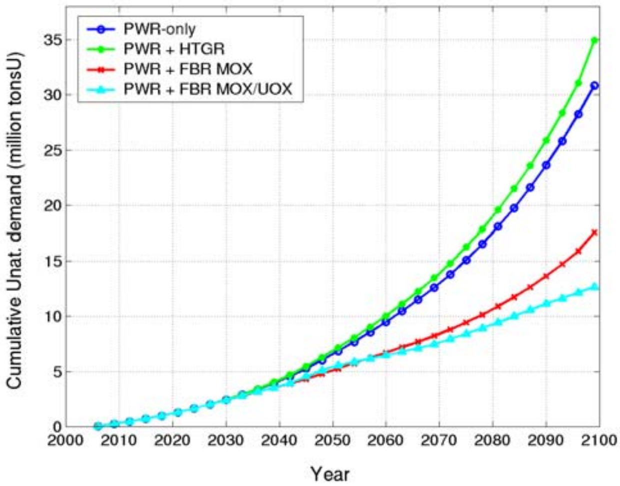


Thanks to the Pu amount issued from PWR SNF reprocessing, the FBR deployment kinetics between 2030 and 2040 is about 40 GWe/yr; but afterwards, around 2045, the available Pu is not sufficient to satisfy such a high demand and new PWRs are deployed. In 2100 the proportion of PWR and FBR is nearly the same, about 2800 GWe. In the case of the **PWR+FBR MOX/UOX** strategy (Cf. Figure 4b), the UOX fuel substitutes the lacking Pu. About 180 GWe/yr. between 2045 and 2055 and over 200 GWe/yr. in the period 2080-2100 are fed by UOX fuel. In 2100 all FBRs are fed with MOX fuel and the entire nuclear fleet is composed by FBR (the last PWRs deployed in 2029 being shut-down in 2089).

The cumulative U demand reduction with FBR with respect to the once-through PWR-only is shown on Figure 5. Not only the cumulative demand in 2100 is higher with PWR, but a considerable amount of U is engaged and will be consumed in the following 60 yrs (Cf. Table 3). The engaged amount in 2100 is reduced by a factor 2 in the **PWR+FBR MOX** strategy (in which only half of the nuclear fleet is composed of PWR in 2100) and is equal to 0 in the **PWR+FBR MOX/UOX** strategy (the whole fleet in 2100 being composed by MOX FBR).

Thus, MOX FBR allows already a considerable reduction with respect to the PWR-only strategy. Furthermore, UOX FBR allows satisfying a higher nuclear demand, ensuring complete sustainability (this is obtained by a temporary higher consumption of the U resource between 2040 and 2060, as shown in Figure 5).

Figure 5: Cumulative natural uranium consumption in the WEC-A3 scenario.



<u>Sensitivity analysis</u>

The hypotheses for the reference strategy (BG=0.2, FBR deployment in 2030, extra-core time of 4 yrs. and Pu-only multirecycling) have been chosen in the logic of a moderate optimism concerning the industrial progress expected over the XXIst century.

Nevertheless, a modification of each one of these parameters may strongly impact the results of the reference strategy:

- An increased BG would allow a higher FBR deployment kinetics, thus reducing the PWR installed capacity and, hence, the natural U consumption;
- In the case of a postponed FBR deployment after 2030, the increased PWR capacity will play unfavorably on the natural U resource;
- An increased extra-core time with respect to the reference value of 4 yrs. would raise the extra-core Pu amount, thus reducing the FBR deployment kinetics;
- The Minor Actinides (MA) management option: the adoption of a MA transmutation strategy (homogeneously mixed with Pu) would allow a higher BG and savings on Pu and natural U. This aspect is counterbalanced by higher doses associated with the fresh fuel and the SNF, as well as safety concerns concerning the reactor design and its operation.

Only the sensitivity to the BG and the FBR deployment date is presented Table 2. Nevertheless, it has to be emphasized that the other items may strongly influence the results of the reference strategy, as it was shown in previous studies [2, 8].

As expected, sensitivities are rather high, with a maximum of 4-5 MtonsU (the amount of *Identified Resources*!). Nevertheless, these values are small if compared to the saving on natural U with respect to the PWR-only strategy.

Table 2: Sensitivity of the cumulative natural uranium demand in 2100 (+ engagement for PWRs) to the FBR's deployment date and the BG (in MtonsU).

Case	2030; BG = 0.2 (Reference)	2040; BG = 0.2	2030; BG = 0.3
PWR-only	31.7 (+30.8)		
PWR + FBR MOX	17.6 (+15.0)	18.3 (+18.1)	15.1 (+10.9)
PWR + FBR MOX/UOX	12.7	16.7	10.5

5.3.2. Comparison between WEC-A3, Low and Bauquis

Figure 6 shows a comparison of the cumulated natural uranium consumption in the three growth scenarios in case of FBR deployment. The Bauquis scenario, whose growth is the highest in the first half of the century, clearly shows the advantage of the **PWR+FBR MOX/UOX** over the **PWR+FBR MOX** strategy (the natural U consumption is well stabilized in 2100 at 9.2 MtonsU). Furthermore, it has to be recalled that in the strategy in which PWRs are still installed in 2100 a considerable U amount is engaged to ensure their feed over their lifetime (Cf. Table 3).

Figure 6: Cumulated natural uranium consumption with the mixed PWR-FBR strategies.

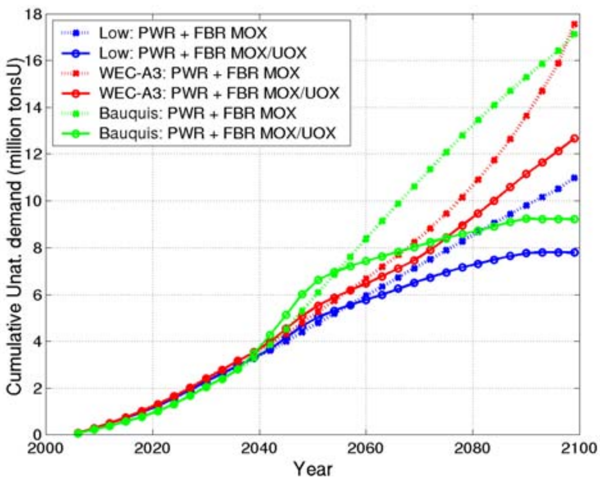


Table 3: Cumulative natural uranium demand in 2100 (+ engagement for PWRs) in MtonsU.

Scenario	Low	WEC-A3	Bauquis
PWR-only	23.0 (+14.1)	31.7 (+30.8)	32.7 (+19.3)
PWR + HTGR	25.2 (+15.9)	34.9 (+34.6)	36.1 (+21.8)
PWR + FBR MOX	11.0 (+2.5)	17.6 (+15.0)	17.1 (+2.3)
PWR + FBR MOX/UOX	7.8	12.7	9.2

Hence, only the Low scenario, with a total consumption + engagement of 37 MtonsU is compatible until 2100 with *Conventional Resources + Phosphates* with a PWR-only fleet, whereas in the other scenarios this amount would be roughly comprised between 50 and 60 MtonsU. The once-through PWR+HTGR fleet shows an increased consumption of about 4-7 MtonsU. The deployment of FBRs allows a reduction of a factor 2 in the WEC-A3 and close to 3 in the Low and Bauquis scenarios (in which, because of a lower nuclear demand, the PWR installed capacity in 2100 is much lower and similarly the U amount engaged at the same date). The FBR start-up with UOX fuel allows satisfying a much higher FBR demand, with no PWR start-up after 2030, stabilizing the natural U consumption and allowing a reduction of a factor 5 with respect to the PWR-only strategy in 2100.

5.4. Industrial requirements

Such a relevant growth of the nuclear energy production as the one described in the previous sections needs relying not only on a technological progress on the nuclear reactor design and operation but, of course, on the associated fuel cycle facilities as well: enrichment, fabrication (especially for the FBR MOX fuel), SNF reprocessing for the closed cycles and geological repository (both for the open-cycle SNF and waste produced in the closed cycles). The world reference values in 2005 for each of these cycle operations are listed in Table 4.

Table 4: World reference values in 2005 for the fuel cycle facilities.

Enrichment	Total world capacity (million SWU/yr.)	56
MOX fabrication	Total world capacity (tHM/yr.)	473
SNF reprocessing	Total world capacity (tHM/yr.)	3800
Geol. repository	Total world SNF production (tHM/yr.)	7200

Hence, if the needs in the WEC-A3 scenario are normalized to the 2005 values taken as reference (= 1), the results of Table 5 are obtained, for the years 2050 and 2100, as well as the integrated value over the whole century (e.g. the SWU need in the strategy PWR-only in 2050 will be 4-fold the world installed capacity for uranium enrichment in 2005).

Table 5: Industrial needs in the scenario WEC-A3 for the fuel cycle facilities normalized to the world reference values in 2005 (Cf. Table 4).

	PWR-Only			PWR-HTGR			PWR-FBR MOX			PWR-FBR MOX/UOX		
	2050	2100	Integr. XXIst c.	2050	2100	Integr. XXIst c.	2050	2100	Integr. XXIst c.	2050	2100	Integr. XXIst c.
Enrichment	4	12	412	5	18	607	2	6	229	3	0	209
MOX fabrication	-	-	-	-	-	-	9	34	1070	10	59	1606
SNF reprocessing	-	-	-	-	-	-	31	94	3590	26	50	2637
Geol. repository	3	11	372	2	4	177	0.006[a]	0.019[a]	0.688[a]	0.006[a]	0.017[a]	0.660[a]

a. In case of U and Pu multirecycling, only MAs (plus Actinides loss) are sent to the geological repository.

6. Conclusion

Different world scenarios of nuclear energy evolution were analyzed with the EDF fuel cycle simulation code TIRELIRE – STRATEGIE.

The unknowns on the nuclear energy growth rate and the associated uncertainty on final results are very high, as well as the uncertainty on the amount of U resources and on the fuel cycle hypotheses (FBR breeding gain and deployment date, extra-core time, etc.). Nevertheless, the following conclusion can be drawn: it appears clearly that none of the analyzed fuel cycle technologies fully satisfies simultaneously the requirements concerning sustainability and waste reduction, safety, economics and proliferation resistance.

PWR-only: sustainability and waste reduction are clearly not met. But the once-through cycle is, for the time being, the most economical solution and the only one completely mastered on the industrial scale and, furthermore, it ensures a good proliferation-resistance.

PWR-HTGR: if the same general conclusions apply also to the HTGR once-through cycle, some drawbacks with respect to the PWR-only cycle occur (higher natural U and enrichment need because of the higher fresh fuel enrichment).

PWR+FBR MOX: the deployment of FBRs, thanks to the cycle closing, allows a reduction of a factor 2 to 3 on natural U in 2100 with respect to the PWR-only cycle and a very consistent reduction of waste production. The economical savings deriving from reduced natural U, SWU and SNF disposal needs are counterbalanced by the reprocessing cost. Furthermore, a significant industrial effort in reprocessing facility construction is required to fulfill an integrated need over the XXIst century equal to almost 4000-fold the 2005 world capacity.

PWR+FBR MOX/UOX: the deployment of FBRs with UOX fuel in case of Pu lack allows:

1. Increased natural U savings (a factor 5 with respect to the PWR-only strategy in 2100);
2. Flexibility in satisfying even high demand scenarios with a cumulative U consumption which is stabilized in 2100 at a value which is well below the amount of *Conventional Resources*, 9.2 for Bauquis and 12.7 MtonsU for the WEC-A3 scenario, thus ensuring complete long-term sustainability;
3. Lower enrichment need (the 2005-2100 integrated SWU demand is reduced by a factor 2 with respect to **PWR-only** and 10% with respect to the **PWR+FBR MOX** strategy).

Finally, it has to be recalled that the last strategy is not only the most efficient from the point of view of the uranium utilization, but it is also the most likely to be adopted, in particular by those countries, (e.g. Asian countries) that did not accumulate a sufficient Pu stockpile with thermal reactors and are now turning to nuclear energy and to FBR in order to satisfy very high demand growth rates. In this context, the need for high Breeding Gain to satisfy high demand scenarios has been clearly underlined. Nevertheless, BGs higher than 0.2 seem difficult to achieve without fertile blankets. Hence, either a reduction of the proliferation resistance should be accepted as the price to pay to achieve sustainability, either specific measures should be undertaken to develop proliferation-resistant fertile blankets.

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