# Deployable nuclear fleet based on available quantities of uranium and reactor types - the case of fast reactors started up with enriched uranium

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# Deployable nuclear fleet based on available quantities of uranium and reactor types – the case of fast reactors started up with enriched uranium

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**Abstract –** *International organizations regularly produce global energy demand scenarios. To account for the increasing population and GDP trends, as well as to encompass evolving energy uses while satisfying constraints on greenhouse gas emissions, long-term installed nuclear power capacity scenarios tend to be more ambitious, even after the Fukushima accident. Thus, the amounts of uranium or plutonium needed to deploy such capacities could be limiting factors.*
*This study first considers light water reactors (LWR, GEN III) using enriched uranium, like most of the current reactor technologies. It then examines the contribution of future fast reactors (FR, GEN IV) operating with an initial fissile load and then using depleted uranium and recycling their own plutonium. However, as plutonium is only available in limited quantity since it is only produced in nuclear reactors, the possibility of starting up these Generation IV reactors with a fissile load of enriched uranium is also explored.*
*In one of our previous studies, the uranium consumption of a third-generation reactor like an EPR™ was compared with that of a fast reactor started up with enriched uranium (U5-FR). For a reactor lifespan of 60 years, the U5-FR consumes three times less uranium than the EPR and represents a 60% reduction in terms of separative work units (SWU), though its requirements are concentrated over the first few years of operation.*
*The purpose of this study is to investigate the relevance of U5-FRs in a nuclear fleet deployment configuration. Considering several power demand scenarios and assuming different finite quantities of available natural uranium, this paper examines what types of reactors must be deployed to meet the demand.*
*The deployment of light water reactors only is not sustainable in the long run. Generation IV reactors are therefore essential. Yet when started up with plutonium, the number of reactors that can be deployed is also limited. In a fleet deployment configuration, U5-FRs appear to provide the best solution for using uranium, even if the economic impact of this consumption during the first years of operation is significant.*

## I. INTRODUCTION

At the current rate at which fuel is consumed, the natural uranium resources identified so far will be sufficient to meet our needs for the next hundred years[1]. However, most organisations in charge of defining energy-related scenarios consider a considerable increase in international nuclear power generation to meet the significantly increasing global energy demand, as well as to comply with climate constraints to reduce greenhouse gas emissions. Due to the growing nuclear reactor fleet in many countries, it is assumed that resources will therefore be depleted more rapidly.

Within the scope of this study, we therefore selected various global nuclear power deployment scenarios.

These scenarios have been applied to analyse what type of reactors must be deployed to meet the global demand: light water reactors (LWR) using uranium-235 ($^{235}$U) or fast reactors (FR) using uranium-238. However, a sufficient amount of plutonium is required to start up FRs and plutonium is produced in water reactors such as pressurised water reactors (PWR) (≈ 1% of the mass of spent fuel). In the event that no Pu is available, the only solution is to start up FRs with uranium enriched in $^{235}$U (U5-FR).

This paper first reviews the static comparison of the total uranium consumption of a LWR with an U5-FR. We then analyse the advantages provided by such reactors within a nuclear reactor fleet development configuration.

Therefore, the first part of this paper assesses the quantities of uranium consumed for the different scenarios under investigation and according to the reactor types being developed.

In the second part of this paper, different limits are imposed on the global uranium supply in order to clearly define the issues related to the necessary resources. The type of reactor required to meet the demand is clearly stated for each limit and each scenario.

## II. STUDY CONDITIONS

### II.A. Prospective scenarios[2]

To carry out this prospective study, we needed to define assumptions with respect to the evolving energy demand and the deployable nuclear technologies available within the century. These assumptions are detailed below.

In the energy field, needs must be defined several years in advance or even several decades in advance so as to plan the construction of infrastructures and meet the demand. This forward-looking approach particularly applies to nuclear power: firstly because a reactor is designed to operate for about 60 years; secondly because waste management issues, like partitioning and transmutation, must be assessed.

We thus chose several IIASA scenarios[3] which provide the energy mix forecast over the 21st century.

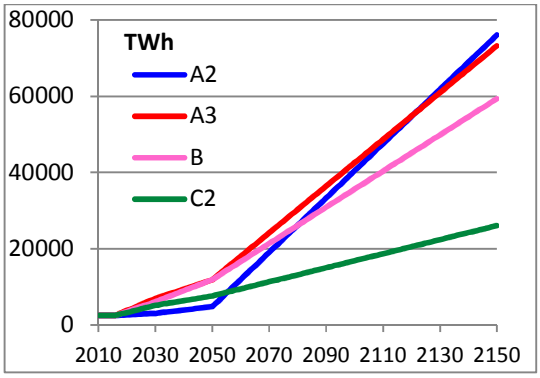



**Fig**. 1: IIASA scenarios: requested electronuclear generation

• A2 is a strong global growth scenario of around 2.7% per year, with the preferred short-term use of oil and gas resources. Nuclear energy represents 4% of world energy demand in 2050 and 21% in 2100.

• A3 is also a strong global growth scenario with a more gradual introduction of nuclear energy than in scenario A2; nuclear energy represents around 11% of world energy demand in 2050 and 22% in 2100.

• B is a business-as-usual world growth scenario during the 21st century (around 2% per year).

• C2 is a scenario that has strong intentions to protect the environment against global warming. It corresponds to a low global demand, though nuclear energy represents around 12% of world demand for primary energy in 2050; this is almost twice as much as it represents today.

The IIASA scenarios consider a strong increase in the world demand in primary energy. Even if the nuclear power share is less than 20%, it supposes a rather significant increase in the nuclear installed capacity.

### II.B. GRUS model

The GRUS[i] model using STELLA[4.] software was developed to calculate nuclear power configurations within various electricity demand scenarios while taking into account the complexity of the nuclear system (large number of stocks, flows and variables, numerous interactions, time scales, and different reactor technologies).

In the model, we defined:

• Initial conditions (raw material stocks, kind and number of reactors and the capacities of facilities)

• Key parameters (facility unit costs, cost of resources, reactor investment and operating costs, and technical characteristics of reactors)

• Electricity demand versus time.

The simulation determined the nuclear fleet required to meet the yearly electricity demand according to the available resources and diverse costs.

### II.C. Reactor types

Four types of reactors were considered in this study:

• PWRs, which are representative of the current reactors in service (GEN II).

• EPRs™ (Evolutionary Power Reactors), which are representative of Generation III water reactors (GEN III).

• FRs, which are representative of Generation IV fast reactors (GEN IV) for which a standard start-up with a Pu load (Pu-FR) is possible. It will also be possible to start them up with enriched uranium if no Pu is available (U5-FR). After several years, such reactors will become identical to reactors started up with Pu, once they will have produced the Pu required for their operation.

[i] GRUS is a French abbreviation which translates as “uranium resource management with Stella software”

*II.C.1. Technical characteristics*

TABLE 1 lists the reactor characteristics that were taken into consideration. U5-FRs have the same characteristics as Pu-FRs in terms of power, load factor and burn-up due to the fact that they become Pu-FRs after ten years.

TABLE 1
Reactor characteristics

| | PWR | EPR | FR | |
|---|---|---|---|---|
| | | | BG[ii] =0 | BG= 0.2 |
| Gross electrical output (GWe) | 1.01 | 1.62 | 1.45 | |
| Efficiency (%) | 33 | 36 | 40 | |
| Burn-up rate (GWd/t) | 45 | 60 | 123 | |
| Mass of heavy metal (t) | 81 | 126 | 51 | |
| Load factor (%) | 77 | 90 | 90 | |
| Enrichment in $U_{235}$ (%) | 3.7 | 4.9 | - | |
| Pu in core (t) | - | - | 12 | |
| %Pu in spent fuel (%) | 1.17 | 1.34 | 23.5 | 28.2 |

TABLE 2 compares $^{235}U$ requirements for EPRs and U5-FRs.

TABLE 2
U-235 requirements

| | Unit | EPR-type PWR[iii] | U5-FR[5] |
|---|---|---|---|
| $^{235}U$ enrichment | % | 4.9 | 14.4 |
| Mass of $^{235}U$ in core | Tonnes of $^{235}U$ /GWe | 3.9 | 8 |
| Reloading | Tonnes of $^{235}U$ /GWe/year | 0.78 | 1.4[iv] |

[ii] BG= breeding gain

[iii] We chose the characteristics of the EPR for comparison with an SR (assumptions may differ in relation to reference [5]). The figures are given in relation to an equilibrium cycle.

[iv] For the first 5 reloads of an U5-FR. The U5 enrichment is given for the first core: it constanly decreases as the U5-FR becomes a Pu-FR

*II.C.2. Assumptions for introducing fast reactors*

In the model, only PWRs are deployed up to 2040. Thereafter, different assumptions were applied when introducing new reactors:

• All new reactors are still PWRs (EPR type) for the whole century with the once-through option.

• Fast reactors (FRs) are installed as long as plutonium is available. When plutonium is not available, either PWRs or FRs started up with enriched uranium can be installed.

## III. URANIUM CONSUMPTION

### III.A. Consumption comparisons for PWRs and U5-FRs

Certain results presented during the FR13[6] conference are recalled in this section.
In this specific case, we have considered an electric utility intending to build a FR without a sufficient amount of Pu. At present, the electric utility can decide whether to build a PWR or a FR started up with enriched uranium. At the end of the reactor's service life (60 years), it can be considered in both cases that the electric utility will have a sufficient amount of Pu to start-up a new FR. The necessary amount of Pu corresponds to two cores: the first core and an equivalent quantity for the first few reloads until Pu from the first core is extracted and recycled for the following loads.

Choosing either reactor will lead to the development of next generation of FRs.

Here, we have considered an open-cycle EPR with the first core and annual reloads using enriched uranium.

We considered that reloads for a U5-FR were performed on a 1/5 basis as the remaining fuel stays in the core for slightly more than 5 years. It is assumed that the cycle lasts 5 years (cooling time after unloading until the manufacture of a new sub-assembly, which can be loaded into the reactor). Enriched uranium must therefore be provided for the first core and the first 5 reloads as the following reloads will be done with the Pu produced by the FR.

TABLE 3 specifies the material flows for the different stages of the fuel cycle under consideration, as well as the enrichment requirements for the reactor lifespan when the price of natural uranium is of €100/kg for the reactor's entire service life (flows vary depending on the price of natural uranium through optimisation of the tails assay, with $U_{nat}$ at €100/kg, the optimised content of depleted uranium is 0.23% of $^{235}U$). Year 0 corresponds to the year the reactor is commissioned.

Over the reactor's 60-year lifespan, it can be seen that the U5-FR uses three times less uranium than the EPR and requires 60% fewer SWUs. Yet if we compare the fuel requirements over the first 7 years of operation, the U5-FR uses twice as more natural uranium and 2.5 times more SWUs than the EPR.

TABLE 3
Annual flow of materials (tonnes) and enrichment requirements (million SWU) for 1 GWe

| | EPR | | | FR | | |
|---|---|---|---|---|---|---|
| Year | Flow of natural uranium | MSWU | Flow of uranium enriched at 4.9% | Flow of natural uranium | MSWU | Flow of uranium enriched at 14.4% |
| -2 | 769 | 0.65 | | 1,628 | 1.67 | |
| -1 | 154 | 0.13 | 80 | 293 | 0.30 | 56 |
| 0 | 154 | 0.13 | 16 | 293 | 0.30 | 10 |
| 1 | 154 | 0.13 | 16 | 293 | 0.30 | 10 |
| 2 | 154 | 0.13 | 16 | 293 | 0.30 | 10 |
| 3 | 154 | 0.13 | 16 | 293 | 0.30 | 10 |
| 4 | 154 | 0.13 | 16 | 161 | 0.17 | 10 |
| 5 | 154 | 0.13 | 16 | | | 6 |
| 6 to 57 | 154 | 0.13 | 16 | | | |
| 58 | | | 16 | | | |
| 59 | | | | | | |
| Total | 9,844 | 8.27 | 1019 | 3,256 | 3.34 | 111 |

### I.A. Uranium consumption of a global nuclear reactor fleet

This section compares the global uranium consumption for meeting the different nuclear power demand scenarios described in II.A according to the reactors being considered. We have already shown that the nuclear industry cannot entirely rely on LWRs[7]. However, the amount of plutonium available for developing the fourth generation of reactors is also a limiting factor[8].

Until 2040, only GEN III reactors are deployed, as it is considered that GEN IV reactors will only be technically available as from that date. After, two cases were considered:

• Case 1 in blue: as many Pu-FRs as possible are installed depending on Pu availability and the fleet is then completed with EPRs.

• Case 2 in red: as many Pu-FRs as possible are installed and the fleet is then completed with FRs started up with enriched uranium.

Fast reactors can be self-sufficient reactors (solid line curves) or breeder reactors with a regeneration gain of 0.2 (dotted line curves).

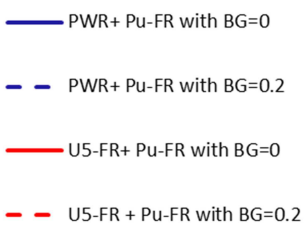



Fig 2 indicates the accumulated uranium consumption for scenario A3.

In Fig. 3, we have added "committed uranium" to the consumed uranium, i.e. uranium for the future reloading of reactors which are currently in operation.

It has been observed that by favouring U5-FRs with respect to LWRs, it is possible to practically halve the total consumption of uranium in 2150. With breeder reactors, it is even possible to stabilise the overall uranium consumption. A sufficient amount of Pu is therefore available to only develop Pu-FRs.

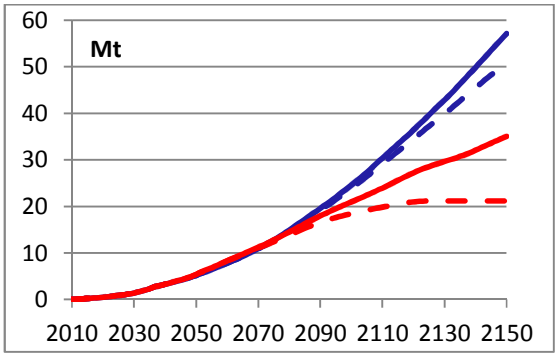



Fig. 2: Scenario A3- Total consumed $U_{nat}$

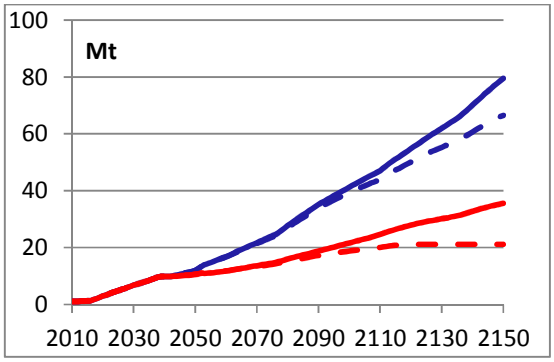



Fig. 3: Scenario A3- Total consumed + committed $U_{nat}$

TABLE 4 to TABLE 7 indicate the total consumption of uranium (consumed uranium in red, consumed + committed uranium in black) for the four different demand scenarios in 2050, 2100 and 2150.

Regardless of the scenario, in 2050, it is observed that the amount of consumed uranium is slightly greater with U5-FRs than with EPRs (see III.A). The excessive consumption for U5-FRs at the start of their service life, compared to EPRs, is thus noted. However, when also considering committed uranium, uranium savings have already been observed.

In 2100, savings start to be significant especially in terms of committed uranium.

In 2150, a significant decrease in the overall uranium consumption is noted when favouring the development of U5-FRs and in some situations it is even halved. In some cases, the quantities of consumed $U_{nat}$ and consumed + committed $U_{nat}$ are identical, which means that no currently operational reactor requires uranium.

TABLE 4
$U_{nat}$ consumed and committed to scenario A2 in 2050, 2100 and 2150

| Scenario A2 | | 2050 | | 2100 | | 2150 | |
|---|---|---|---|---|---|---|---|
| | | GR=0 | GR=0,2 | GR=0 | GR=0,2 | GR=0 | GR=0,2 |
| Total consumed $U_{nat}$ | EPR + Pu-FR | 2.5 | 2.5 | 20 | 20 | 55 | 51 |
| Total consumed and committed $U_{nat}$ **(Mt)** | EPR + Pu-FR | 4.7 | 4.7 | 37 | 36 | 80 | 70 |
| Total consumed $U_{nat}$ | U5-FR + Pu-FR | 2.7 | 2.7 | 16 | 14 | 32 | 19 |
| Total consumed and committed $U_{nat}$ **(Mt)** | U5-FR + Pu-FR | 4.6 | 4.6 | 17 | 15 | 32 | 19 |

TABLE 5
$U_{nat}$ consumed and committed to scenario A3 in 2050, 2100 and 2150

| Scenario A3 | | 2050 | | 2100 | | 2150 | |
|---|---|---|---|---|---|---|---|
| | | GR=0 | GR=0.2 | GR=0 | GR=0.2 | GR=0 | GR=0.2 |
| Total consumed $U_{nat}$ | EPR + Pu-FR | 5.2 | 5.2 | 25 | 24 | 57 | 51 |
| Total consumed and committed $U_{nat}$ (Mt) | EPR + Pu-FR | 12 | 12 | 41 | 39 | 79 | 66 |
| Total consumed $U_{nat}$ | U5-FR + Pu-FR | 5.4 | 5.4 | 21 | 18 | 35 | 21 |
| Total consumed and committed $U_{nat}$ (Mt) | U5-FR + Pu-FR | 11 | 11 | 22 | 19 | 36 | 21 |

TABLE 6
$U_{nat}$ consumed and committed to scenario B in 2050, 2100 and 2150

| Scenario B | | 2050 | | 2100 | | 2150 | |
|---|---|---|---|---|---|---|---|
| | | GR=0 | GR=0.2 | GR=0 | GR=0.2 | GR=0 | GR=0.2 |
| Total consumed $U_{nat}$ | EPR + Pu-FR | 5.0 | 5.0 | 21 | 20 | 47 | 42 |
| Total consumed and committed $U_{nat}$ **(Mt)** | EPR + Pu-FR | 12 | 12 | 35 | 33 | 64 | 53 |
| Total consumed $U_{nat}$ | U5-FR + Pu-FR | 5.2 | 5.2 | 18 | 16 | 29 | 18 |
| Total consumed and committed $U_{nat}$ **(Mt)** | U5-FR + Pu-FR | 10 | 10 | 19 | 17 | 30 | 18 |

TABLE 7
$U_{nat}$ consumed and committed to scenario C2 in 2050, 2100 and 2150

| Scenario C2 | | 2050 | | 2100 | | 2150 | |
|---|---|---|---|---|---|---|---|
| | | GR=0 | GR=0.2 | GR=0 | GR=0.2 | GR=0 | GR=0.2 |
| Total consumed $U_{nat}$ | EPR + Pu-FR | 3.5 | 3.5 | 11 | 11 | 22 | 19 |
| Total consumed and committed $U_{nat}$ **(Mt)** | EPR + Pu-FR | 7.4 | 7.4 | 18 | 16 | 30 | 23 |
| Total consumed $U_{nat}$ | U5-FR + Pu-FR | 3.7 | 3.7 | 10 | 10 | 15 | 10 |
| Total consumed and committed $U_{nat}$ **(Mt)** | U5-FR + Pu-FR | 7.0 | 7.0 | 11 | 10 | 15 | 10 |

We remarked the brief excess consumption of uranium when U5-FRs are deployed rather than light-water reactors (see Fig. 4, example of scenario A3). We wanted to check if this could be penalising in terms of the annual demand, whether for uranium extraction or enrichment.

The brief increase due to the deployment of U5-FRs can be seen in Fig. 5 with respect to the uranium demand and in Fig. 6 for enrichment needs. It can be seen that the increase is nevertheless reasonable since several U5-FRs are included in the global fleet which is mainly composed of light-water reactors.

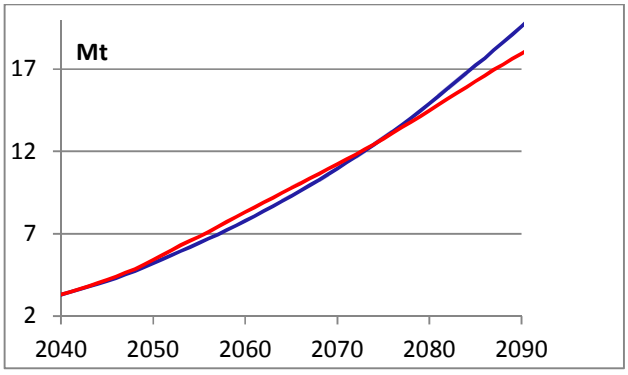



Fig. 4: Accumulated consumption of$U_{nat}$, Scenario A3

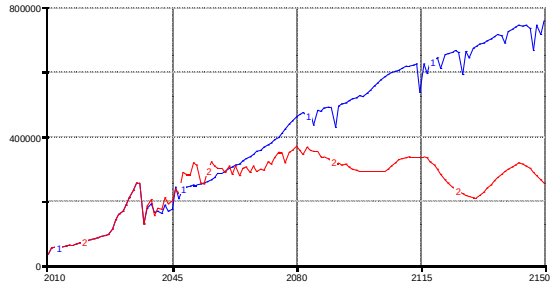



Fig. 5: Annual demand for $U_{nat}$, Scenario A3

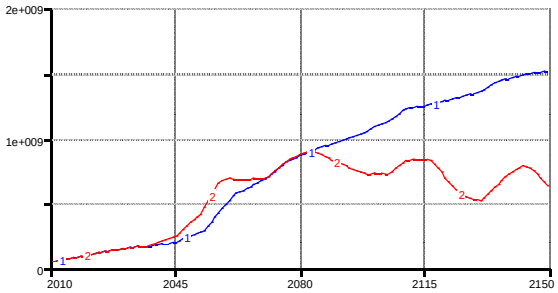



Fig. 6: Annual demand for SWU, Scenario A3

## IV. POTENTIAL NUCLEAR CAPACITY

Up until now, we have considered it possible to extract the quantity of uranium required as long as the extraction cost is paid. This assumption seems realistic in a market context and it considers that resources diluted in seawater are accessible, though it does not take into account procurement issues which could arise once all conventional resources have been exhausted.

In this section, we approach the issue of resources in a different manner by considering the available quantities of natural uranium as limited.

### IV.A. Different available quantities of uranium

We have considered four different quantities of available natural uranium:

• 10 Mt corresponding to the order of magnitude of identified uranium resources[1].

• 20 Mt corresponding to the order of magnitude of conventional resources, added to 4 Mt of uranium extracted from phosphates[9].

• 40 Mt corresponding to the order of magnitude of conventional resources, added to about 22 Mt (former estimate of uranium extracted from phosphates).

• 80 Mt, which takes into account the possibility of mining exploration finding substantial new resources; there is nothing to support this figure which is based on a very optimistic view of a textbook example.

### IV.B. Reactor deployment assumptions

As mentioned in the previous section, Generation IV reactors will be technically available from 2040.

We have added an extra constraint: when the committed uranium (i.e. taking into account the needs of operational reactors throughout their services lives) exceeds one of the limits in question, it will be impossible to build a new reactor requiring enriched uranium (i.e. PWRs, EPRs and U5-FRs in our case). The only reactors that can be built once this limit has been reached are fast reactors started up with plutonium. Considering that plutonium has to be produced and is not available in unlimited quantities, one day we will no longer be able to build enough reactors and thus no longer match supply to demand.

### IV.C. Deployment of EPRs only

Fig. 7 to Fig. 10 show the quantity of energy that the nuclear system may produce for each scenario depending on the limits on available uranium quantities.

Demand is indicated in black, while nuclear power generation as a function of the limited quantities of uranium is indicated in colour.

The different colour curves drop off from the black curve. This moment corresponds to the date at which the uranium limit is equal to the quantity of uranium already consumed, added to the committed quantity for the future operation of reactors already in service.

When nuclear power generation reaches 0, this limit quantity of uranium has been consumed.

It is clear that nuclear power will not be sustainable with only Generation III reactors. Scenario C2, which requires only 25,000 TWh in 2150, is the only case where demand could be met despite more than 40 Mt of uranium required (consumed + committed) at this date and already 20 Mt in 2100.

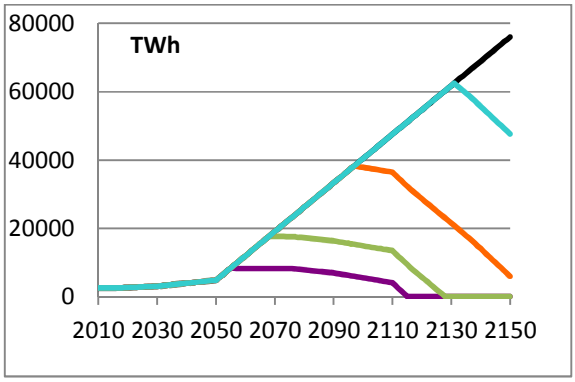


Fig. 7: Electronuclear production by EPRs only, Scenario A2

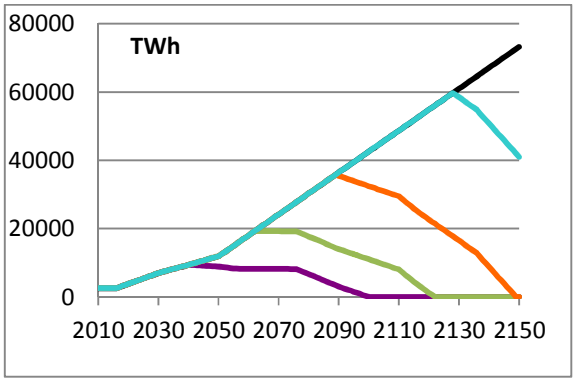


Fig. 8: Electronuclear production by EPRs only, Scenario A3

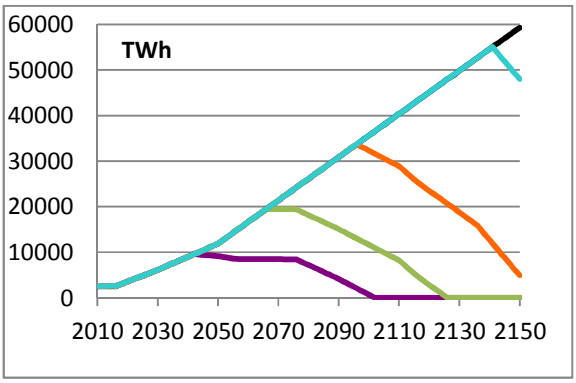


Fig. 9: Electronuclear production by EPRs only, Scenario B

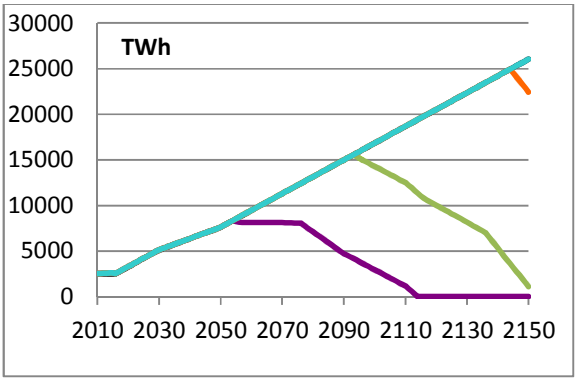


Fig. 10: Electronuclear production by EPRs only, Scenario C2

### IV.D. Deployment of self-sufficient or breeder Pu-FRs from 2040

Since we have shown that only light water reactors do not meet the nuclear power generation demand as laid out in the prospective scenarios, we included Generation IV reactors from 2040. We considered these reactors with a first fissile Pu load, which means that Pu availability will therefore be an important parameter for their deployment.

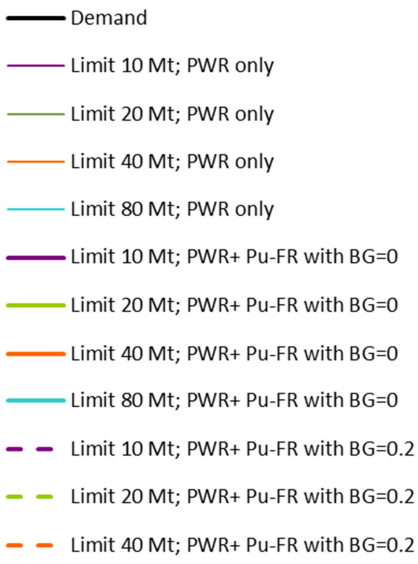
Fig. 11 to Fig. 14 show the nuclear power generation that can be expected in relation to the type of reactors deployed and as a function of the quantity of uranium believed to be extractable.

Contrary to the case where only light water reactors would be deployed (thin line), here it would be possible to maintain nuclear production regardless of the case considered. Despite this, most of the cases remain far from meeting demand.

It can be seen that an installed power plateau is reached after a certain time with self-sustained reactors (solid lines), which corresponds to the quantity of Pu produced in PWRs based on the available quantity of uranium. This represents a FR installed power capacity of about 70 GWe/Mt of uranium.

It can also be seen that production is significantly increased with breeder reactors (dashed lines), especially in the next century. Yet more than often, demand is not met.

For the first three high-demand scenarios, about 80 Mt and self-sufficient reactors at least are needed to meet demand. More than 20 Mt is needed with breeder reactors for scenario C2 which has a lower demand, or slightly more than 40 Mt in the case where only self-sufficient reactors are used.



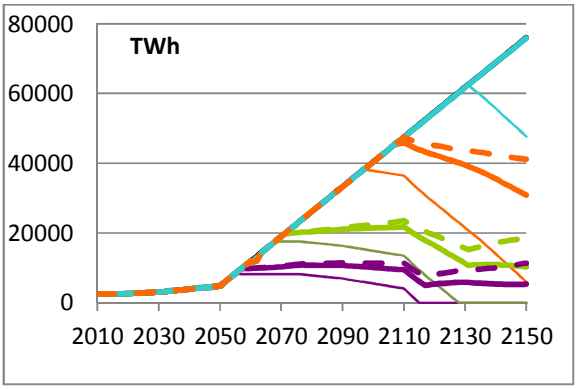


Fig. 11: Production by EPRs and Pu-FRs, Scenario A2

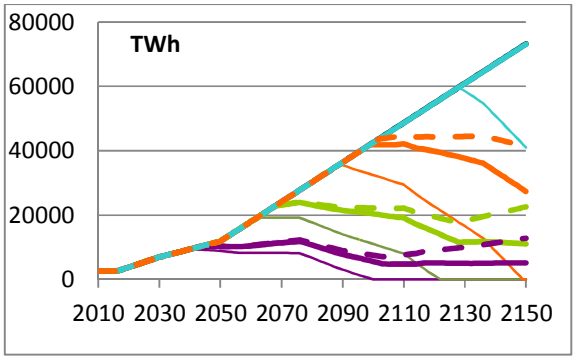


Fig. 12: Production by EPRs and Pu-FRs, Scenario A3:

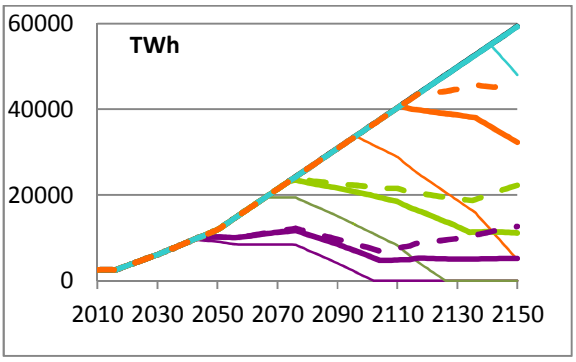


Fig. 13: Production by EPRs and Pu-FRs, Scenario B

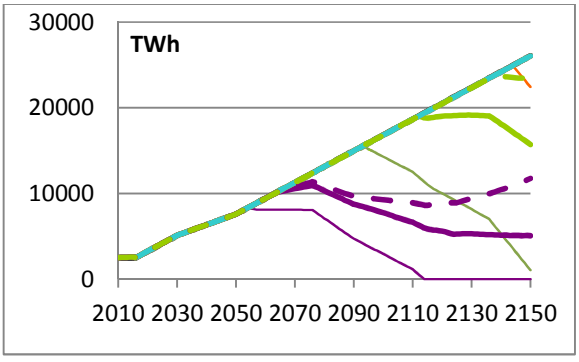


Fig. 14: Production by EPRs and Pu-FRs, Scenario C2

### IV.E. Deployment of self-sustaining and breeder Pu-FRs and U5-FRs

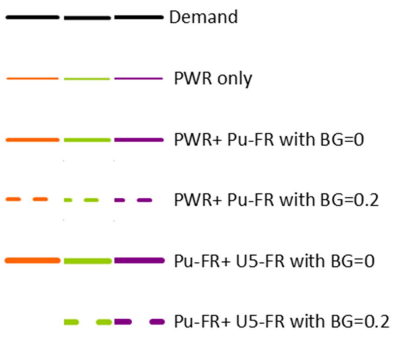
We established in the paragraph above that including FRs was not sufficient to meet the demand in many cases, especially when the uranium quantities were limited (< 80 Mt).

We have already shown that a U5-FR consumes three times less natural uranium than an EPR. We also remarked that a reactor fleet including the deployment of U5-FRs instead of EPRs made it possible to reduce the accumulated consumption of uranium by two.

Now the objective is to see whether such reactors are capable of meeting the demand despite the limits imposed on the quantities of available uranium.

Technically speaking, these reactors will be available from 2040, as is the case for Pu-FRs. From this date, priority will be given to deploying Pu-FRs if Pu is available, otherwise we will resort to using U5-FRs.

We have restricted ourselves to referring to the curves of the two extreme scenarios (A3 and C2).




The following conclusions were reached for scenario A3:

• With only 10 Mt of available uranium (Fig. 15), it is practically all consumed before FRs are integrated. The advantage of U5-FRs is therefore insignificant.

• For other uranium limits, particularly 20 and 40 Mt (Fig. 16 and Fig. 17) the relevance of deploying U5-FRs rather than EPRs is clearly visible when plutonium is not readily available. If only 20 Mt of uranium is available, then breeder reactors are needed to meet the demand. With 40 Mt of uranium, self-sufficient reactors are adequate to meet the demand.

• If 80 Mt of uranium is available, it has already been seen that Pu-FRs are sufficient to meet the demand.

Similar conclusions could be drawn for scenarios A2 and B.

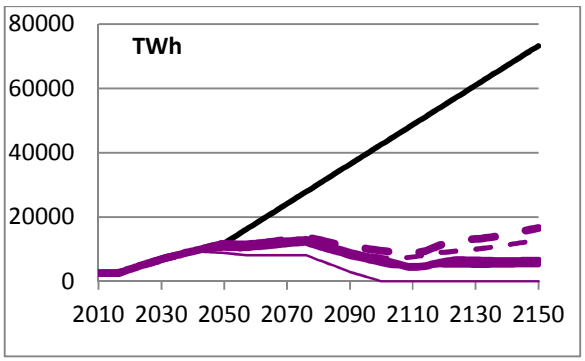



Fig. 15: Electronuclear production, Scenario A3 with **10** Mt

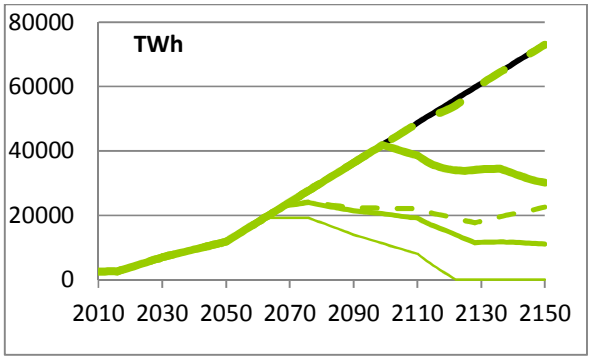



Fig. 16: Electronuclear production, Scenario A3 with **20** Mt

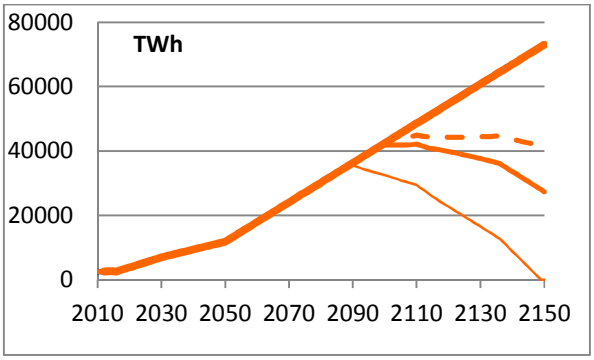



Fig. 17: Electronuclear production, Scenario A3 with **40** Mt

The following conclusions were reached for scenario C2:

• As this scenario was generally less ambitious in terms of nuclear power generation, the 10 Mt of uranium was not consumed and committed in 2040. The positive contribution of U5-FRs is thus visible since the demand is met with these reactors when they are in breeder configuration, while remaining below 10 Mt of uranium consumption (Fig. 18).

• When only 20 Mt of uranium is available (Fig. 19), breeder Pu-FRs are practically sufficient. Self-sufficient U5-FRs are just barely required.

• Self-sufficient FRs or PWRs were sufficient for 40 and 80 Mt of uranium respectively, as had already been concluded previously.

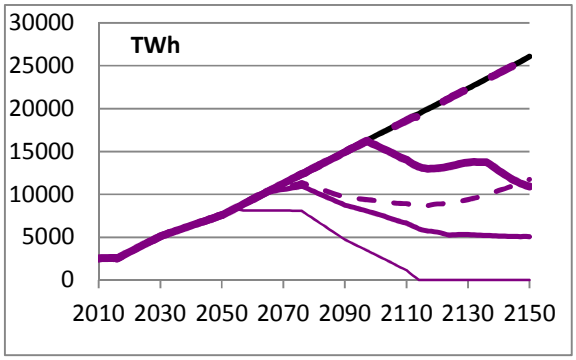



Fig. 18: Electronuclear production, Scenario C2 with **10** Mt

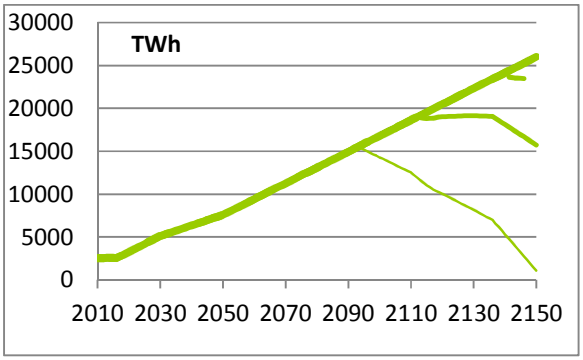



Fig. 19: Electronuclear production, Scenario C2 with **20** Mt

## V. CONCLUSION

The purpose of this study was to determine what types of reactors and fuels would be needed to meet different nuclear power production scenarios.

Nuclear power is not sustainable on the basis of light water reactors only, unless the demand remains relatively limited (scenario C2= 25,000 TWh in 2150 ≈ 3000 GWe) and we have large stocks of available uranium (more than 40 Mt). The fourth generation of reactors is therefore essential if we wish to meet demand. Yet the quantities of available plutonium do not always enable us to deploy as many fast reactors as required and light water reactors are often necessary to supplement the nuclear reactor fleet to meet the demand.

Self-sufficient configurations of Generation IV reactors would make it possible to meet scenario C2 with a uranium consumption of more than 40 Mt all the same. Almost 80 Mt of uranium is required for higher-demand scenarios.

When breeder configurations are applied to Generation IV reactors, only 20 Mt of uranium is required for scenario C2. The demand will remain partially unmet for the three other scenarios.

We therefore imagined the deployment of fast reactors started up with enriched uranium to remedy the lack of available plutonium. This type of reactor consumes three times less uranium than an EPR-type light water reactor. We assumed that uranium was only needed for the first core and the first few reloads, but then the plutonium produced by the reactor would be used thereafter.

Thanks to these reactors, the nuclear reactor fleet would be able to meet demand in scenarios A2, A3 and B (from 60,000 to 80,000 TWh in 2150 ≈ 7500 to 10,000 GWe). These reactors would have to be breeders in the case there is only 20 Mt of uranium, or only self-sufficient with 40 Mt of uranium available.

In the case of only 10 Mt of uranium, these Generation IV reactors - which will be technically available in 2040 - will arrive too late since this quantity of uranium will have been consumed prior to this date. It is only scenario C2 that can be met with U5-FRs in breeder configuration, with 10 Mt of uranium available.

In terms of resource savings, U5-FRs are seen to be the best solution for using limited quantities of uranium while providing maximum nuclear power. Unfortunately, though uranium consumption is three times less for U5-FRs than that for an EPR-type light water reactor, it is nevertheless consumed at the start of the reactor's life span which represents a significant economic disadvantage. For this reason, economic aspects will hinder the deployment of this type of reactor.

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