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Impact of a possible large scale development of SMRs on natural uranium consumption and deployment of nuclear power worldwide

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Abstract

Small modular reactors (SMRs) are on the rise, especially because of their expected modularity, shorter construction time, and low capital costs compared to large Generation III nuclear reactors; they are also likely to be more uranium intensive. In such case, we studied the impact of SMR development on uranium resources and its effect on fast reactor deployment using GRUS, a system dynamic-based numerical tool. Based on nuclear energy demand scenarios up to the year 2150, we show the evolution of the nuclear fleet by reactor type, along with the associated uranium consumption. In all our scenarios and even without SMRs, the global development of nuclear energy in 2150 already exceeds conventional uranium resources. On top of it, in a nuclear fleet made of EPRs and FRs, SMRs could lead to an additional uranium requirement of about 25%. Furthermore, the non-reprocessing of SMRs spent fuels would reduce plutonium stocks, what would impact the deployment of fast reactors and cause an additional demand of natural uranium of more than 10%. Finally, the SMRs, by accelerating the use of uranium resources, increase its cost and bring forward the date of competitiveness of fast reactors from a few years to several decades. The results indicate that to ensure the sustainability of nuclear power with SMRs, a particular attention must be paid during the design phase of such modular reactors to uranium consumption and fuel reprocessing.

KEYWORDS: SMR, natural uranium, resources, nuclear sustainability

1. Introduction

Small Modular Reactors (SMRs) are currently very well perceived: more than 70 concepts are currently being studied over the world, representing a 40% increase between 2018 and 2020, according to the IAEA's SMR book [1]. This enthusiasm is due to the expected advantages of SMRs in terms of acceptability, financing and construction time. They also offer other benefits for module manufacturing, simplification of circuits associated with a passive safety approach.

As shown in the SMR book [1], there is a large variety of reactors: some simply have a lower unit power than traditional ones, others are modular, some are easily movable (on barges for example), and others are micro-modules of less than 10 MW_e. Depending on the objectives of electricity or heat production, different technologies are being developed, from Light Water Reactors (LWR) to generation IV reactors (GEN IV).

Among the most advanced SMRs, we find LWR-type ones, which benefit from all the experience acquired by this type of reactor and fuel. Their characteristics span over a large range of values. An important one is that they could be more uranium-intensive: for the same energy supply as large LWRs, the need for natural uranium is more likely to be greater. It is mainly due to an objective of simple fuel management*, a small reactor size that amplifies neutron leakage, and lower efficiency.

Energy forecast scenarios, such as those by IIASA [2], [3] or IPCC [4], estimate that the size of the world's nuclear fleet will increase significantly by 2050 and probably beyond. In such a case, the need for natural uranium (NU) will increase and will be further amplified by the deployment of uranium-intensive SMRs. Several studies, such as [5]–[7], have shown that significant development of nuclear power on a global scale would lead to severe constraints on the availability of uranium resources and plutonium (Pu) inventories; impacting the horizon of competitiveness of Fast Reactors (FRs), as shown in [8]. Strong development of LWR-SMRs could then be accompanied by an increased pressure on Natural Uranium

* The number of reactor shutdowns can be reduced using less reload batches; so the load factor is increased, but the drawback is the use of a greater amount of natural uranium.

(NU) resources, because of their uranium-intensive nature, but also because spent fuels from SMRs could not be reprocessed, which seems to be the implicit rule among designers.

Assessing the availability of uranium resources requires a comprehensive representation of the nuclear fuel cycle. At a minimum, it should include NU resources, enrichment and fuel fabrication, different reactor technologies, and consider the reprocessing of spent fuel. To study the fuel cycle, many codes have been developed, as shown and classified by the review [9]. These codes differ by the spatial framework (global, national, or smaller), the resolution of isotope evolution, and the reprocessing of spent fuels.

In this work, we analyze the economic aspect of uranium resources to satisfy the demand for nuclear electricity, using *GRUS*[†], a model developed by the CEA I-Tésé institute. The results focus on the impact of the development of SMRs on the uranium resources, plutonium production and the economic competitiveness of FRs compared to LWRs. In comparison with large LWRs, SMRs have two main impacts: a higher NU consumption and a greater Pu production per unit of energy produced. Based on simplified modeling of the global nuclear system, this study seeks to capture key trends in the system and provide orders of magnitude. The following section details the framework, methodology and main assumptions of this work.

2. Methodology

2.1. General framework

This work is using the *GRUS* tool, a system dynamics-based model representing nuclear fleets. *GRUS* was developed in the early 2000s by CEA[‡] to assess, among others, the depletion of uranium resources [5], [10], cost evolution and competitiveness among reactors technologies [8]. Indeed, it models different reactor types with their fuel cycle including uranium consumption and plutonium production. It is a prospective tool that can describe the evolution of the world's nuclear fleet, NU consumption and cost over a long-term horizon – here 2150. The structure of the tool has been detailed in the article [8], only its main features are reminded here.

Model presentation:

The *GRUS* model is a simulation tool developed with the STELLA software [11]. It takes as input parameters prospective scenarios of nuclear energy demand. From initial conditions representing the world nuclear fleet in 2010 as well as uranium resources, *GRUS* estimates the evolution of the fleet until 2150, with a time step of one year. At all times, energy supply must be equal to or greater than demand. The power installed is therefore determined by the demand for nuclear energy. The choice of reactor technology to be installed is driven by the resource availability (uranium and plutonium), and if chosen, also by their cost.

In this study, 4 reactor types are modeled[§]. Their characteristics are provided in Table 1:

- **Pressurized Water Reactor (PWR):** They are representative of the second generation (GEN II) currently in service.
- **Evolutionary Pressurized Reactor (EPR):** They are representative of the third generation (GEN III) of water reactors
- **Small Modular Reactor (SMR):** These reactors' characteristics will be further detailed in this paper. They are representative of GEN III pressurized light-water reactors and chosen with a net electrical power of 400 MWe. Additional details about ongoing SMR projects can be found in the SMR book from IAEA [1].
- **Fast Reactor (FR):** They represent the fourth generation (GEN IV) and are sodium fast reactors. They are started with a plutonium (Pu) load. For the sake of simplicity, they are considered self-sufficient, producing the same amount of Pu as they consume during operation.

[†] *GRUS* is a French acronym translated as “*Uranium Resources Management with Stella environment*”.

[‡] The French Alternative Energies and Atomic Energy Commission .

[§] Several reactor types are not modeled. For example Boiling Water Reactor consumption is very close to PWR and other types such as Candu, RBMK or AGR are not widely spread. These reactors are modeled like PWR Gen II for the uranium consumption.

We consider PWRs as a former generation, there is no new construction plan. From 2018 they are replaced by EPR and SMR. The development of FRs is subject to two possibilities. On the one hand, the date of first commissioning can be set, as it is the case in results *Parts 1* and *2*. On the other hand, the competitiveness of fast reactors can also be calculated, based on their costs – it is done in the last *Part 3*. In such case, a Levelized Cost of Electricity (LCOE) per nuclear technology is performed at each time step of the simulation. It leads to the construction of the cheapest reactors, from the LCOE point of view.

In both cases, the development of FRs is limited by the plutonium availability – the whole inventory is committed either to the reactors or to the fuel cycle.

By construction, GRUS is a model whose calculations are performed quickly and allow parametric analyses. In this study, we do not aim to go into the details of the different stages of the fuel cycle, but rather to show orders of magnitude and main trends, highlighting the impact of a parameter on the system. The following paragraph details the main assumptions of this work.

Main assumptions of this study:

1. We assume that spent fuels from LWRs are fully reprocessed. By reprocessing, we mean the recovery of plutonium from the spent fuels.
2. The date of the first industrial operation is set for 2030 for the SMRs.
3. For the sake of simplicity, we choose to model the penetration of SMRs proportionally to EPRs development. For this, we introduce x_p , the proportion of SMRs installed per unit of LWR needed. For example, for every unit of power needed, there is a proportion x_p of SMR installed and $(1 - x_p)$ for EPR, where $x_p \in [0, 1]$. This means that the share of SMR among all LWR tends to x_p , once all EPRs built before 2030 are shut down.
4. Based on a literature review of prospective nuclear power demand scenarios, we choose two poles apart scenarios from IASA [12], named A3 (*strong demand*) and C2 (*low demand*). References of this review are not detailed here but the results are presented in Figure 1. A3 and C2 scenarios are based on a 1998 analysis; to ensure their consistency they were compared to more recent prospective scenarios such as those presented in studies [2]–[4]. Figure 1 shows that the two considered scenarios are representative of current prospective works that do not foresee a nuclear phase-out or rely on a technological breakthrough. Scenarios are ranging from 2010 to 2100. From 2100 to 2150 lines are extended with linear extrapolation.

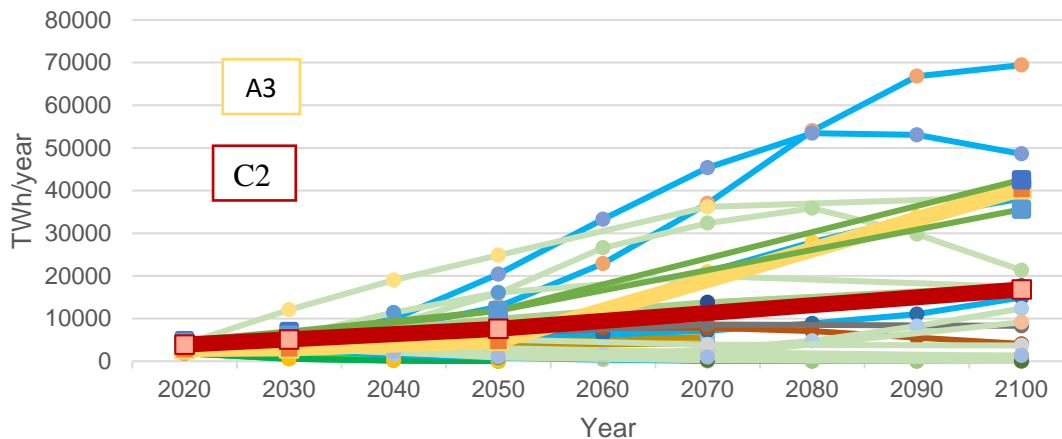


Figure 1: Literature review of nuclear power demand prospective scenarios, ranging from 2010 to 2100. A3 (yellow, strong demand) and C2 (red, low demand) are the two scenarios from IASA [12] used. The additional lines represent scenarios not detailed in this study.

Input parameters

With GRUS, nuclear reactors are modeled with few parameters. We list below those that define NU consumption and Pu production:

- **Power:** Net electrical output power of the reactor.
- **Efficiency:** Amount of electric power production for each unit of thermal power.
- **²³⁵U enrichment:** Percentage of the U-235 isotope in fresh fuel.

- **Heavy metal:** Mass of heavy metal in the core.
- **Burn-up:** Thermal energy released per mass unit of heavy metal in fuel.
- **kp:** *Load-factor* ratio between the energy actually produced over a given period and the energy that would have been produced by operating at maximal power over the same period.
- **Pu in IF:** Percentage of plutonium in the Irradiated Fuel (IF). Those values result from calculations carried out in CEA for EPR-kind UOx fuel assembly enriched at 4.95%.

We consider that EPRs and SMR are operated with UOx fuel assembly, enriched with 4.95% of U-235. We present in Table 1 the parameters chosen to characterize the reactors and the deduced natural uranium consumption.

The NU consumption per unit of energy produced by SMRs is a crucial characteristic of these reactors, but data are lacking in the scientific literature. The SMR Book [1] shows that the NU consumption could span over a large range of values. Values presented in Table 1 correspond to SMRs that consume twice as much NU per unit of energy produced as EPRs and produce nearly 40% more Pu. This could be the case, for example, of some systems presented in the SMR book.[1].

Table 1: Technical characteristics of SMRs, EPRs and FRs considered in the study.

	Power (GWe)	Efficiency (%)	²³⁵ U enrichment (%)	Burn-up (GWd/t)	kp (%)	Heavy metal (tons)	Pu in IF (%)	Ref	NU consumption tU/GWhe**
SMR (SMR 3)	0.4	36	4.95	30 ^{††}	90	59	0.9 ^{††}	[1]	40 ^{††}
EPR	1.65	36	4.95	60	90	128	1.3	[13]	20
FR	1.45	40	–	81	90	87.8	–	[14]	–

The impact of the NU consumption of SMRs is assessed in Part 1: Impact of the uranium consumption. We carry out a sensitivity analysis and consider different reactors, whose characteristics ‘burn-up’ and ‘Pu in irradiated fuel’ vary such that their NU consumption is equal to that of the EPRs, 50% and 100% higher. The values used are given in Table 2.

Table 2: Characteristics of the three SMRs studied in the sensitivity analysis of Part 1. SMR 3 corresponds to the reactor technology considered in parts 2 and 3.

	Burn-up (GWd/t)	NU consumption (t/GWhe)	Overconsumption/EPR (%)	Pu in IF (%)
SMR 1	60	20	0	1.3
SMR 2	40	30	50	1.1
SMR 3	30	40	100	0.9

For the sake of simplicity, SMRs efficiency is chosen as equal to the one of EPRs and is not varying. However, according to the SMR Book [1], it is most likely to be smaller and would generate a greater NU consumption per unit of energy produced.

Additional fast reactor characteristics: In addition to Table 1 and to calculate the Pu inventory, we assume that there are 12 tons of Pu in the first core and almost the same amount for the first reloads.

2.2. Model outputs and results organization

To summarize, the GRUS model takes as input reactor characteristics, prospective nuclear energy demand scenarios. In response, it returns for each time step the cumulative quantity of natural uranium consumed, the plutonium stocks and the installed capacity of each nuclear technology. Throughout this paper, we compare the NU consumption of various nuclear fleets. By means of comparison, the NEA/IAEA Red Book estimates in 2020 the conventional resources – identified and undiscovered – to 15 million tons of uranium (MtU).

** To calculate this NU consumption we have taken 0.25% of ²³⁵U for the tails. Nevertheless in our model, the tails assay is optimised, function of the NU, enrichment and conversions costs, therefore evolving over time .

†† The *Burn-up*, *Pu in IF* and *NU consumption* are subject to a sensitivity analysis presented in the Part 1.

To account for the uncertainties in SMR characteristics and their deployment, energy demand and resource availability, several sensitivity analyses are performed. This study is organized into three parts that address the following points:

1. Sensitivity analysis of SMRs deployment on uranium consumption according to assumptions of SMRs unitary NU consumption.
2. In the case of uranium-intensive reactors, what is the impact of SMRs on uranium resources and plutonium inventories?
What is the impact of not reprocessing spent fuels from SMRs?
3. What is the impact of SMRs on the competitiveness horizon for fast reactors?

In the first two parts and to simplify the approach and focus on the effects of other parameters, the competitiveness of fast reactors is assumed such that the first reactors are commissioned in 2080. In the last part only the competitiveness date is calculated based on the LCOE of each type of reactor, including investment costs, operating costs and the fuel cycle.

3. Part 1: Impact of the uranium consumption of SMRs on the global uranium consumption

In this section, we present the impact of different SMR technologies on uranium consumption, based on their consumption of uranium per unit of electricity produced. This analysis is not exhaustive and intends to show the relative differences in the consumption of the world's uranium resources. The effects of additional parameters on the system are assessed in the two parts that follow.

a. Methodology

To underline the impact that could result from SMR development, we place ourselves in a context favorable to nuclear growth that would tend to very large uranium consumption:

- The scenario of strong nuclear deployment (A3) is used.
- A large deployment of SMRs is assumed ($x_p = 30\%$) from 2030.

Within this parametric framework, the three SMRs presented in Table 2 are compared. SMR 1 corresponds to a technology that would consume as much NU as EPR per unit of energy produced[‡]. SMR 2 and 3 are respectively consuming 50% and 100% more NU compared to an EPR.

b. Results and discussion.

Results are presented in Figure 2 and expressed in million tons. It shows the cumulated uranium consumption from 2010 to 2150 for the 3 SMRs described in Table 2.

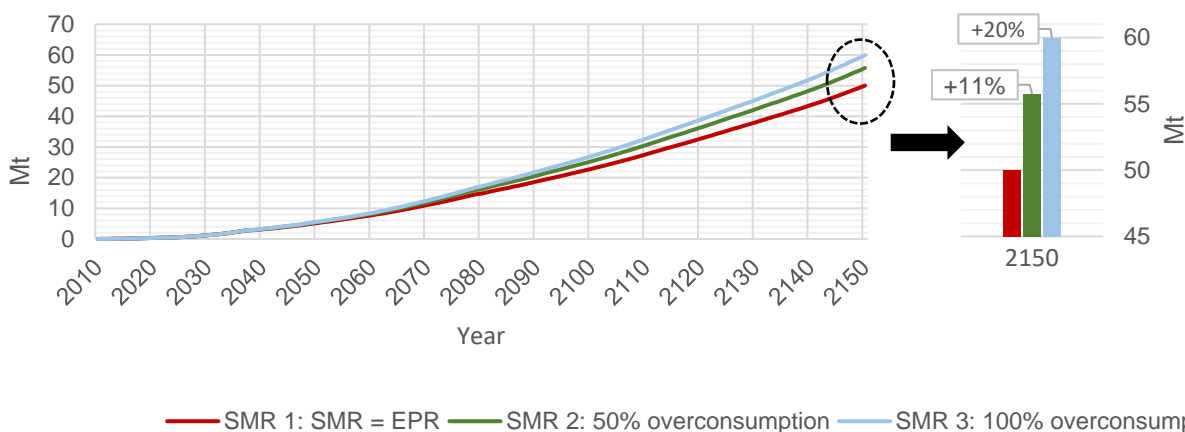


Figure 2: Cumulated natural uranium consumption in the case of a strong deployment of SMRs ($x_p=30\%$) and the strong nuclear energy demand scenario (A3).

[‡] There is a slight difference of NU consumption between cases with SMR 1 and EPRs only. Indeed, the first cores of SMR1 have a higher NU consumption than EPRs for the same installed capacity. That is why there is a consumption of 50 Mt with SMR1 (Figure 2) and 49 Mt with only EPRs (Figure 5 a).

This figure shows that by 2150 and in every case of this strong nuclear power demand scenario, the NU consumption is far above 15Mt, the current estimation for conventional resources. In addition, the development of SMRs which are more uranium-intensive than EPRs would increase the cumulative NU consumption by several million tons. For SMRs consuming 50% more uranium per unit of energy produced (SMR 2), the cumulated NU consumption grows by 11%, and reaches 20% – 10Mt – for SMRs consuming 100% more NU (SMR 3).

This introductory part shows that the consumption of NU per unit of energy produced by SMRs has a first-order impact on the overall NU resources. To evaluate the effects of other parameters, we retain the characteristics of the extreme case, SMR 3.

4. Part 2: Impact of SMRs on Uranium consumption, plutonium production and deployment of FRs

a. Methodology

The results presented are compared to the ‘No-SMR’ situation described below:

‘No-SMR’ case:

The nuclear fleet is here only composed of Gen II PWR in 2010, then followed by EPRs. We assume all spent fuels are reprocessed and from 2080, FRs are developed, using all Pu available. Both strong and low (A3 and C2) power demand scenarios are used (see Figure 1).

To get an intuitive understanding of the model behavior, we present in Figure 3 the evolution of the nuclear fleet by reactor type (Fig. a) and the total power installed (Fig. c), from 2010 to 2150, in the reference case described above. In addition, we present the same results for scenario C2 in Figure b.

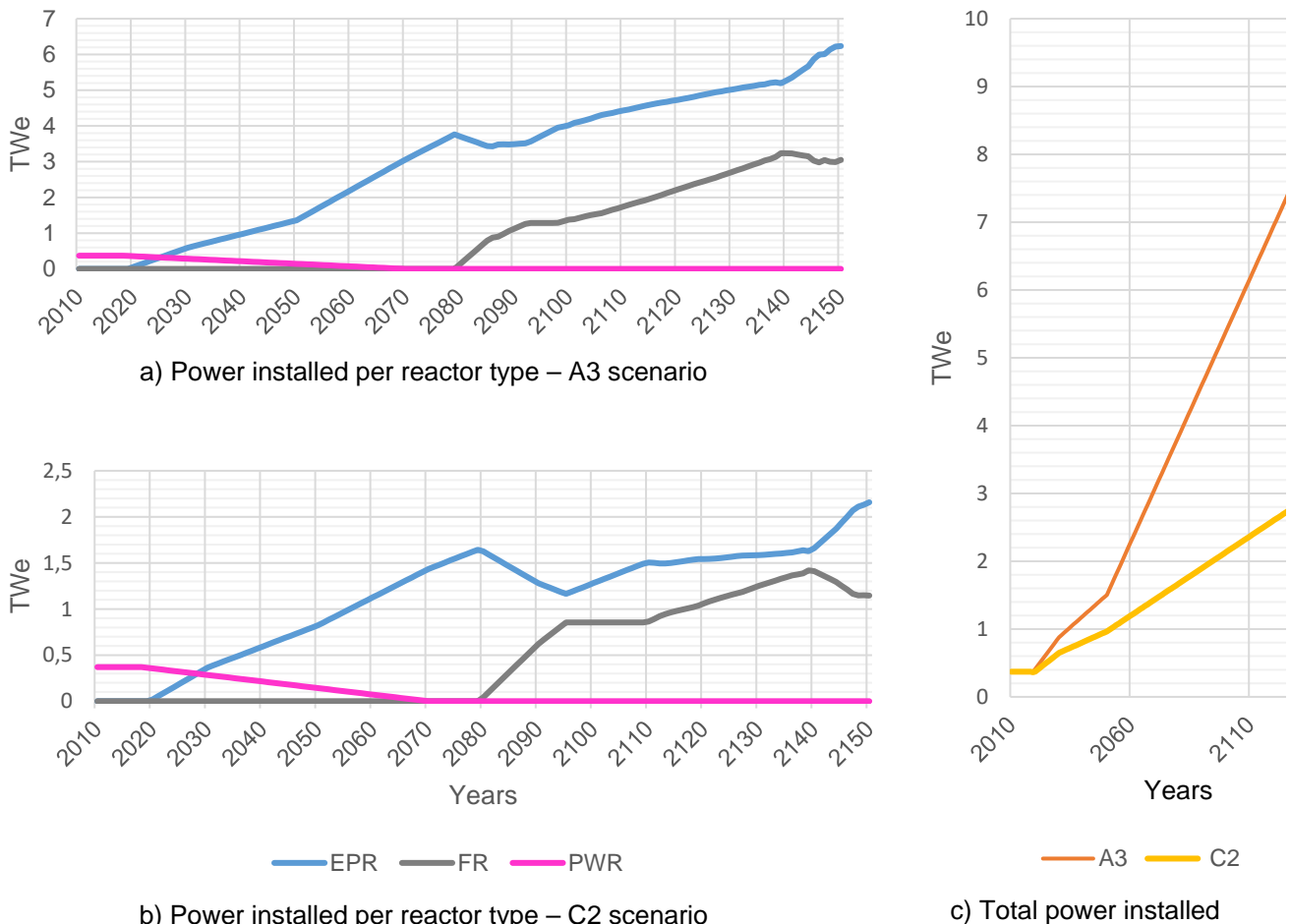


Figure 3: Installed capacity by type of nuclear reactors (a and b) and total power installed (c).

We observe that PWRs (in pink) are replaced after their end of life by EPRs (in blue). From 2080 onward, when is set the first commissioning of FR (in grey), this technology starts to grow. Nevertheless, these

reactors do not replace all EPRs, since there is not enough plutonium to fulfill the entire demand with fast reactors.

In 2140, the first installed fast reactors are reaching their life-end. The old cores must be reprocessed, therefore an additional lot of Pu is in the fuel cycle and not available for FR cores. Since there is no Pu left, some fast reactors are replaced by EPRs^{§§}.

b. Results and discussion

The results presented below are divided into two sections. We first assess the effect of a strong development of SMRs on the NU consumption and evaluate its impact on the nuclear fleet. Over a second phase, we carry out a sensitivity analysis on the penetration rate of SMRs and evaluate the impact of non-reprocessing their spent fuels.

i. Impact of SMR 3 on the nuclear fleet and cumulative uranium consumption:

We assume here that SMRs are widely developed (i.e. $x_p = 30\%$) and compare the results to the ‘No SMR’ case.

Figure 4 presents the impact of SMRs on the development of EPRs and FRs from 2010 to 2150. Full lines give the different reactor types installed when SMRs are not developed, dotted lines when SMRs are installed from 2030. We observe that the development of SMRs enables to install a few more FRs.

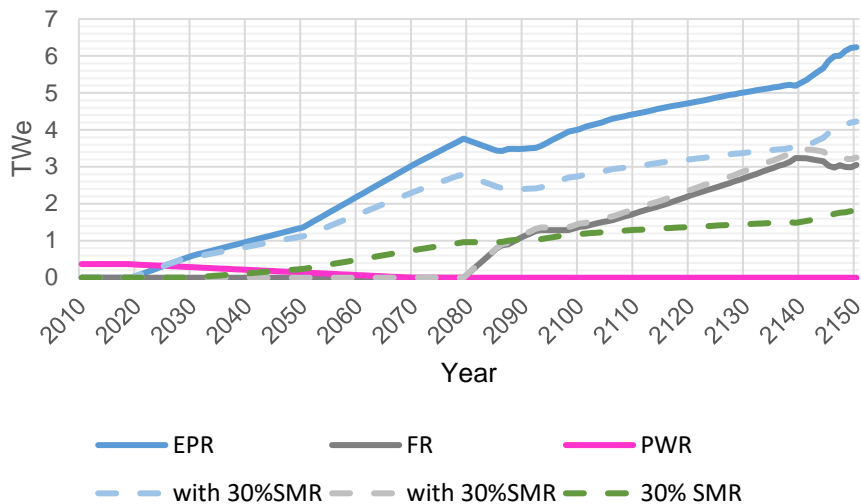


Figure 4: Electrical power installed with EPRs and FRs in the nuclear fleet (full lines) and additionally with SMRs (dotted lines).

To enhance the understanding of the outputs of our model, we investigate the effect of SMRs on different nuclear fleets. The Figure 5 presents the impact of a strong deployment of SMRs ($x_p = 30\%$) on uranium resources in 2150 for two demand scenarios, A3 (Figure a) and C2 (Figure b). Four types of nuclear fleets are compared in this figure, where the cumulative NU consumption from 2010 is given inside the circles:

From top to bottom circles, fast reactors are introduced, and the consumption decrease is materialized with blue arrows:

1. Only EPR: upper left corner.
2. EPR + FR: lower-left corner.

From left to right row, SMRs are introduced. The increase in NU consumption generated is indicated with red arrows.

3. EPR + SMR: upper right corner.

^{§§} This may not be very realistic from an industrial point of view. The installation of the FRs could have been smoothed out or some breeding would have made it possible to have a little more Pu available for the renewal of the reactors.

4. EPR + FR + SMR ; lower right corner.

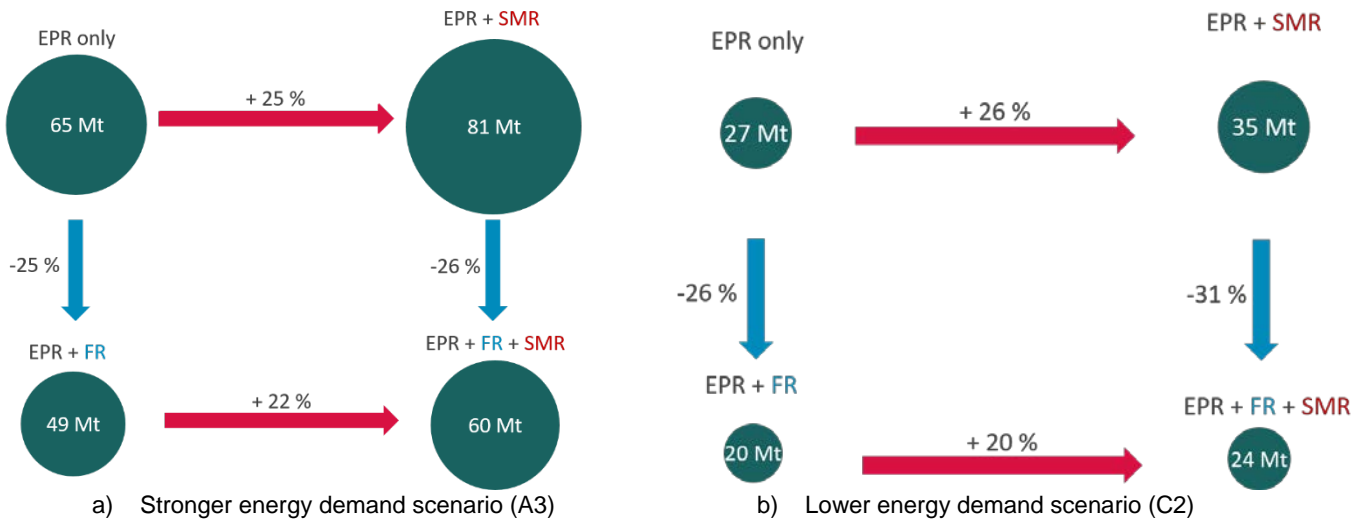


Figure 5: Natural Uranium cumulated consumption in 2150, for four different nuclear fleet scenarios, expressed in million tons. From left to right row, SMRs are installed ($x_p = 30\%$). From top to bottom, FRs are installed.

Figure 5 illustrates the balance of the NU consumption due to the development of SMRs. Results are provided at the horizon 2150.

On the one hand, SMRs increase the NU consumption because of their uranium-intensive character. On the one hand, we see that the development of FRs decreases the need for NU by about 25% (left blue arrows) when developed in a 100% EPR fleet. This drop is even greater (right blue arrows) when FRs are developed along with SMRs. On the other hand, we show that the deployment of SMRs increases the need for uranium by around 25% when compared to a fleet of 100% EPR (upper red arrows). Nevertheless, this increase is only of the order of 20% (lower red arrows) when the fleet is composed of both EPRs and FRs.

Indeed, SMRs consume more NU and produce more Pu. It enables the installation of more FRs and therefore reduces the NU consumption. The development of SMRs has thus a *retroactive effect* on uranium consumption. A strong development of SMRs in a fleet of LWRs and FRs would involve in 2150 a cumulated NU overconsumption of between 4 and 11 Mt, respectively in the case of a low or strong development of nuclear energy. Finally, we observe that the global consumption of a fleet with EPRs, SMRs and FRs is of the same order of magnitude as a fleet of EPRs alone.

Figure 6 shows the distribution of installed power breakdown by reactor technology in the case "EPR+FR", with and without SMRs. The results are calculated at the horizon of 2150, for the strong energy demand scenario A3 and a strong deployment of SMRs ($x_p = 30\%$).

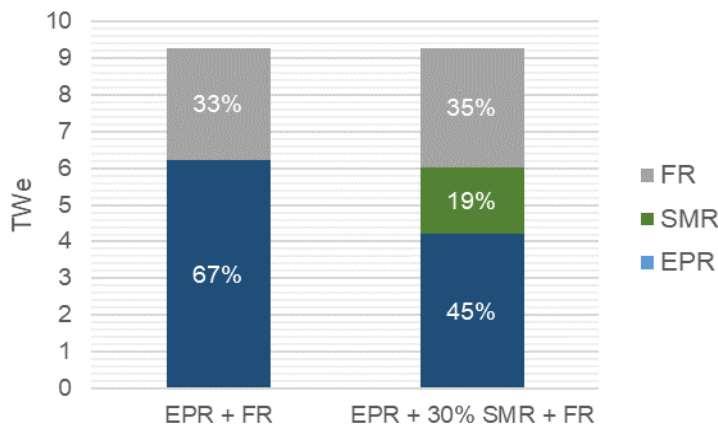


Figure 6: Installed capacity per reactor type in 2150, for the strong power demand scenario A3. The right bar corresponds to a simulation with $x_p = 30\%$

It shows that SMRs, because of their Pu overproduction, enable to install more FRs by an additional 2% – ~ 200 GWe. This greater number of FRs enables to slightly mitigate the need for NU caused by SMRs.

ii. Sensitivity analyses of the SMRs spent fuel reprocessing and penetration rate:

The results presented above are calculated for a strong development of SMRs, assuming that all spent fuels are reprocessed. We now refine this analysis and evaluate the impact of both various penetration rates of SMRs and the non-reprocessing of their spent fuels.

We consider a nuclear fleet with both EPRs and FRs; SMRs are developed with three different penetration rates: 0% corresponding to the absence of SMRs, 10% and 30%. Results are computed for both the strong (A3) and low (C2) energy demand scenarios.

Figure 7 shows the effect of fuel reprocessing on the installed capacity of fast reactors and results are given for the horizon 2150.

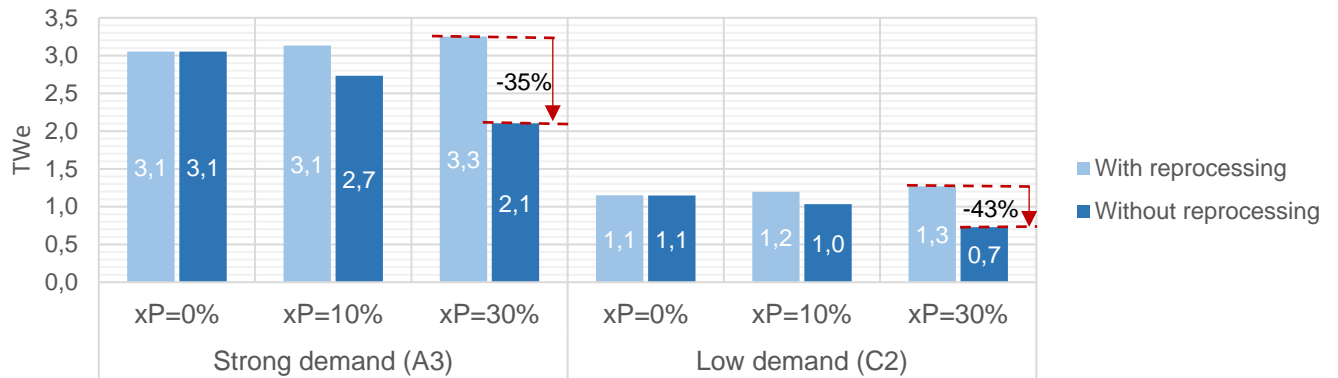


Figure 7: Influence of the reprocessing of the SMRs spent fuels on the FRs installed capacity in 2150.

Similarly, Figure 6 and Figure 7 shows that when Pu is recovered from SMRs spent fuels (light blue bars), the increase in SMRs share is accompanied by a slight increase in the FRs share. Indeed, the recovered Pu enables to install more FRs. The opposite effect – with a greater intensity – is observed when these fuels are not reprocessed (dark blue bars), the increase in SMRs reduces the Pu stocks.

For the same cases, we present in Figure 8 the cumulated NU consumption.

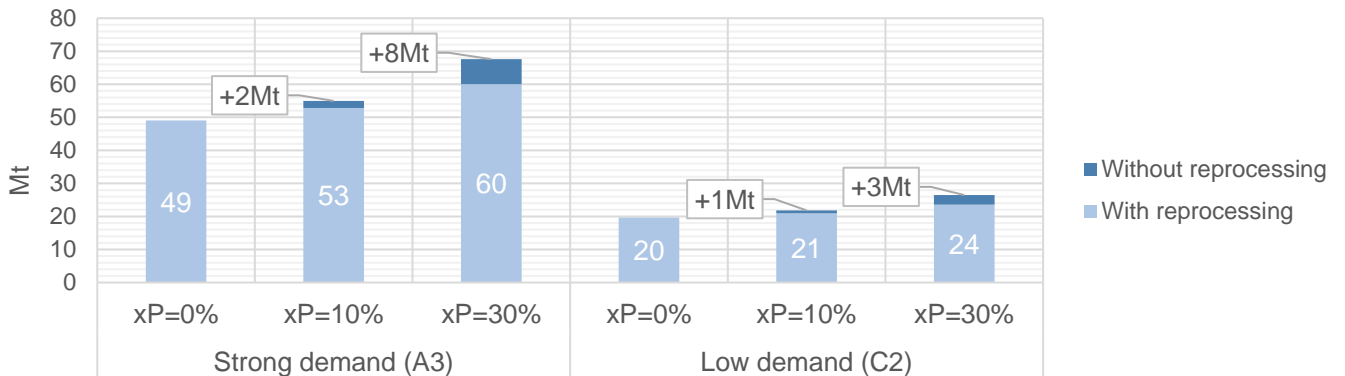


Figure 8: Influence of the reprocessing of the SMRs spent fuels on the cumulative uranium consumption in 2150.

This shows that not recovering Pu from SMRs fuels indeed reduces Pu stocks and limits the development of FRs. It therefore involves an additional need for NU of about 15% – 3 to 8 Mt (respectively for C2 and A3) for the strongest SMRs development. Note that the 'retroactive effect' on the NU consumption due to SMRs development (highlighted in Figure 5) is lost when Pu is not recovered from SMR spent fuels.

5. Part 3: Assessing the competitiveness of fast reactors

In this section, we study the effect of SMRs on the competitiveness of fast reactors. For this purpose, the first commissioning date of FRs is calculated and no longer imposed, as in previous sections.

a. Methodology

The competitiveness of FRs is reached when their LCOE became lower than the one of EPR. When compared with EPRs, we consider that FRs have both *over-investment* and *over-operating* costs which are respectively 1.5 and 1.25 times greater than EPRs.

This LCOE calculation takes as input the NU cost. In GRUS, uranium resource is modeled using long-term supply curve. We construct a simplified model, where the cost of NU is a function of the quantities already mined, as described in Figure 9. This assumption implies that there is no resource limitation, only an increase in cost^{***}. In this work, we use two extreme cases named U_p and U_{op} , respectively pessimistic and optimistic, based on the NEA/IAEA Red Book for the first part of the curves [15]. These curves are only meant to describe extreme scenarios.

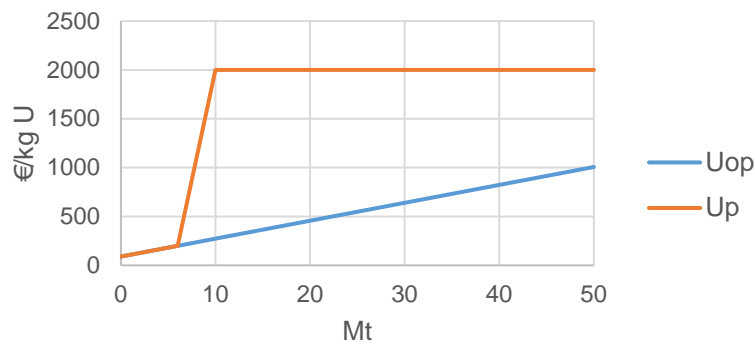


Figure 9: Natural uranium supply curves. It represents the cost per mass unit as a function of the extracted uranium.

In the pessimistic case U_p , the cost increases sharply between 6 and 10 Mt, corresponding to the threshold of identified reserves^{†††}. The optimistic case U_{op} assumes that, as demand increases, conventional resources will be found and exploited.

In this model, we additionally consider the increasing cost of uranium over the operating period of the LWR by defining an average value that represents the cost of all the reloads of an LWR during its operating lifetime. It is detailed in the reference [8].

b. Results and discussion

Results presented in Table 3 show the evolution of the competitiveness horizon of fast reactors, whether the SMR technology is developed or not. Calculations have been made for both nuclear power demand and the two supply curves (U_p and U_{op}). We assume here a strong development of SMRs, i.e. $x_p=30\%$.

Table 3: Competitiveness horizon of FRs , with and without the introduction SMRs ($x_p=30\%$). The calculations are made for the two scenarios of nuclear power demand (A3 and C2) as well as for the two supply curves (U_p and U_{op}).

FRs first commissioning horizon		Nuclear demand scenarios			
		A3		C2	
		No SMR	$x_p = 30\%$	No SMR	$x_p = 30\%$
Natural Uranium Supply Curves	U_p	2060	2054	2078	2065
	U_{op}	2150	2117	FRs not competitive before 2150	

^{***} Note that this modeling does not include the short-term volatility of market prices. Implicitly, this implies the price is equal to the cost of production

^{†††} For modelling purposes, we assume a threshold at 2000 €/kg at which large resources of uranium would be available.

This shows that the strong development of SMRs, leading to an overconsumption and cost increase of NU, makes fast reactors competitive with EPRs, earlier from 5 to more than 30 years.

The effect is greater when the increase in the NU cost is more gradual (U_{op}) or the demand lower (C2). Generally, when the nuclear power demand is strong (A3), the development of SMRs has a smaller effect on the competitiveness of FRs, conversely to a lower power demand (C2). Given this impact, it would be desirable to get more transparency from SMR developers on the expected uranium consumption of their future projects.

Conclusion

In the context of existing studies such as [5] and [8] that have shown that the worldwide development of nuclear power could be limited by the availability of uranium resources and plutonium stocks, we focus here on the impact of small modular reactors on the future nuclear fleet. To this end, we have deliberately considered a reactor technology consuming twice as much natural uranium as the EPR per unit of energy produced, and producing nearly 40% more plutonium.

Even if it is not the main focus of this study, the results recall that a worldwide development of nuclear energy would require quantities of uranium exceeding the known conventional limits, estimated to 15 Mt in 2020 by the NEA/IAEA [15]. This limit is reached for both scenarios before 2150.

If SMRs were to be globally deployed (30% of the LWRs capacity installed) and in the case of uranium-intensive technologies, we list below the main points highlighted in this paper:

- Development of SMRs would lead to an overconsumption ranging between 4 and 11 Mt at the horizon of 2150. These consumptions correspond to a nuclear power installed of respectively 3.3 (C2) and 9.3 TW_e (A3), in the case of a strong development of SMRs
- Moreover not reprocessing spent fuel from SMRs would lead to an additional uranium overconsumption that could reach 3 to 8 Mt in the long range.

In addition, SMRs would impact the development of fast reactors:

- The development of SMRs and the induced overproduction of plutonium (if spent fuels were reprocessed) make it possible to install a larger share of fast reactors – about 2%, or 200 GW_e in the case of a strong global nuclear development. However, this does not compensate for the excess NU consumption due to SMRs.
- The increase in the cost of uranium implied by a faster consumption of the resource could bring forward the date of competitiveness with the EPRs by 5 to 30 years, depending on nuclear development and the availability of uranium resources.

Overall, particular attention must be paid to uranium consumption and the reprocessing of spent fuels from SMRs. We have shown that these parameters have a first-order impact on uranium resources, and thus on the sustainability of nuclear energy.

Limits:

We have presented in this paper the main trends of the system studied and the values provided should be considered as orders of magnitude. Indeed, the calculations are based on a representation of the nuclear system with a low level of detail, and we present an optimistic perspective for the availability of uranium and the development of nuclear power: we do not consider any geopolitical limitation, nor any constraint on the exploitation of raw materials. Moreover, all spent fuel is assumed to be reprocessed, which is far from being the case today.

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