LWR-SFR synergy for a sustainable nuclear fleet: economic relevance and impact on the competitiveness of SFRs

G. Mathonnière[1], S. Gabriel[1], A. Baschwitz[1]

[1]CEA/DAS/I-tésé Paris Saclay University

E-mail contact of main author: gilles.mathonniere@cea.fr

Abstract. The synergy between SFRs and LWRs provides a number of advantages from an economic perspective and it is highly probable that future nuclear fleets that no longer burn natural uranium will be composed of both breeder SFRs and High conversion ratio LWRs using 100% MOX fuels. To use SFR in such a fleet improves their economic competitiveness.

Key Words: LWR-SFR synergy - SFR Competitiveness - High conversion ratio LWR - Sustainability

1. Introduction

To make nuclear energy a sustainable solution for the next thousand years or so, nuclear reactors will be required to produce electricity with depleted uranium only and no longer with natural uranium.

The nuclear research community has been looking for a solution in fast reactors, in particular sodium-cooled fast reactors (SFR). Although the investment cost of SFRs is higher than that of light water reactors (LWR), which explains why there are currently so few SFRs in operation worldwide, the scarcity of natural uranium and its resulting increased cost will eventually make SFRs competitive in relation to LWRs. There will be a place for SFRs in a sustainable energy mix if they also remain competitive in relation to renewable energies (wind and solar), which is probable if system costs are taken into account.

2. Various options for the ever-decreasing use of natural uranium on an asymptotic scale

The final goal is to deploy a nuclear fleet that eventually only uses depleted uranium after having phased out the use of natural uranium on an asymptotic scale.

The fuel cycle is very important in terms of feasibility, but it only plays a secondary role from an economic perspective, with the key parameter being the investment cost of the reactors: the tendency will thus be to deploy a fleet with as few SFRs as possible.

This means it would be better to avoid a 100% SFR fleet and to make use of the complementarity between SFRs and LWRs. Since we do not want this fleet to use natural uranium but only depleted uranium, these LWRs will have to be 100% MOX, with the excess plutonium produced by breeder SFRs being used in these 100% MOX LWRs.

As the relationship between the number of SFRs and the number of 100% MOX LWRs is directly related to the production of plutonium by the SFRs and its consumption in the LWRs, there must simultaneously be an increase in the plutonium (of the same quality) produced in the SFRs and a decrease in the plutonium burned in the LWRs if we wish to increase the proportion of LWRs in the fleet.

This means that we need SFRs that breed as much as possible and LWRs that use as little plutonium as possible, such as LWRs with a high conversion ratio (HCR).

The ideal situation would of course be to have self-sufficient LWRs. This was achieved technically for the first time in a Shippingport pressurised water reactor, which proved to be a moderate breeder [1]. This reactor in its light water breeder (LWBR) configuration reached criticality in 1977 and operated until 1982. However, special equipment had to be used to achieve this breeding performance: fertile thorium rods and a dense array to achieve a hardened spectrum. Having a denser array than in conventional LWRs adversely affects the critical heating ratio and can cause cladding failure. To ensure safe operation and avoid such problems in the case of the Shippingport PWR, the power had to be derated: during this operating period in LWBR mode, the power density of the reactor was 6 times less than that of a present-day PWR.

A 6-fold reduction in the power density of a reactor for which investment + operation accounts for around 80% of the cost per kWh amounts to multiplying the cost per kWh produced by approximately 5 [1], which is prohibitive in economic terms.

Even though it would certainly be possible to do somewhat better today than the Shippingport case, the derating ratio to be applied remains unchanged.

Attempts made in this field with the potentially self-sufficient FLWR concept [2] have been unsuccessful, with thermohydraulic questions proving difficult to overcome. The question is whether HCR LWRs can be relevant in the future by improving their conversion ratio rather than resorting to the self-sufficient mode.

In conclusion, it is not economically viable to have a nuclear fleet that does not use natural uranium with LWRs only. It would be possible to build a 100% self-sufficient SFR fleet, but this is clearly not the best economic solution, which is still to be found in building a fleet with both breeder SFRs and 100% MOX LWRs.

3. Optimal reactor mix for an asymptotic fleet

Given the above considerations, it seems that fairly well-known reactor technologies could be examined: a self-sufficient SFR, a breeder SFR [3] [4] and a 100% MOX EPR. As well as these reactors, SFRs with improved breeding performance will also be considered, but only those in fields which are fairly mature: SFRs with a metal (or carbide or nitride) fuel will not be considered, because even though they have greater breeding potential they are at a less advanced stage of development.

Given that the total breeding gain (TBG) of an SFR with a low sodium void effect (CFV) is around 0.15, it seems possible to increase this to 0.20 or even 0.25 by adding blankets, but without fundamentally changing the design. For example, there is the SFR-025, which as a TBG of 0.25.

With regard to improvements that can be made to the 100% MOX EPR, the two HCR LWRs studied recently at the CEA could be considered: one with a square lattice, HCR-SQU [5],

---

[1] Economically speaking, if we consider that 80% of the cost of a current LWR (investment & operation) is proportional to the installed cost per kWe and that 20% (cycle) is independent of this, then if the power produced were to be divided by 6, the estimated cost per kWh produced by a self-sufficient LWR would be about 6 x 80%+20% = 500% of that of a current LWR.

and the other with a hexagonal lattice, HCR-HEX [5]. These two concepts are evolutionary in that they can operate in an EPR vessel, the main modifications being the in-vessel structures, the fuel and the control absorber rods. They have been defined to be technologically achievable, with the consequence that their performance is limited in terms of conversion ratio.

TABLE I: HCR Main characteristics

	Power (MWe)	Pu inventory (t)	Conversion ratio	Management	Consumption Pu in kg/ TWhe
HCR-SQU	1450	16.2	0.86	¼ 250 EFPD	48
HCR-HEX	1450	19.86	0.923	¼ 375 EFPD	23

All the reactors to be examined, together with their related plutonium consumption, are listed in the following table:

TABLE II: Pu consumption for different reactors

Sodium Reactors	Pu consumption (kg/TWhe)	Water Reactors	Pu consumption (kg/TWhe)
SFR-000	0	EPR-100	65
SFR-015	-25	HCR-SQU	48
SFR-020	-33	HCR-HEX	23
SFR-025	-42		

EPR-100 is the 100% MOX EPR. SFR-015 corresponds to an SFR V2b reactor, and SFR-000 is its self-sufficient version.

Note 1: the production of plutonium depends on its isotopic quality. It can range between -20 and -25 kg/TWhe for the SFR-015. The value of 25 kg was chosen, which corresponds to the asymptotic conditions.

Note 2: the production of the other SFRs has been inferred from SFR-015, assuming it is proportional to their TBG.

Note 3: the plutonium consumption of the HCR LWRs has been established with the “Pu2035” isotopic composition, which corresponds to the average amount of plutonium estimated to be available in France in 2035. Since the plutonium from SFRs is better quality, increased performance (lower Pu consumption) is expected.

4. Asymptotic fleets studied

The F1 fleet, comprising self-sufficient SFRs only, will be examined first.

This will be followed by the F2 fleets, comprising various types of SFR together with 100% MOX EPRs.

We will then examine the F3 fleets with basic SFRs (SFR-015) but in which the 100% MOX EPRs will be replaced by HCR LWRs.

Finally, we will examine the F4 fleets in which the SFRs will have higher performance levels and the 100% MOX EPRs will be replaced by HCR LWRs.

All these fleets are listed below. The proportion of SFRs in the fleet balance is given for each fleet. This is determined simply by the balance between plutonium production in the SFRs and plutonium consumption in the LWRs:

TABLE III: Fleet examinated

Fleet	Reactors in the fleet	Proportion of SFRs (%)
F1	SFR-000	100
F2	SFR-015; EPR-100	72
F2a	SFR-020; EPR-100	66
F2b	SFR-025; EPR-100	61
F3a	SFR-015; HCR-SQU	66
F3b	SFR-015; HCR-HEX	48
F4	SFR-020; HCR-SQU	59
F4a	SFR-020; HCR-HEX	41
F4b	SFR-025; HCR-SQU	54
F4c	SFR-025; HCR-HEX	36

It can be seen that it is possible to reduce the proportion of SFRs even further than in the F2 configuration: even in the fairly realistic case of an SFR with a TBG of 0.20 and a square HCR, there will already only be 2/3 (64%) SFRs in the fleet, which is definitely moving in the right direction for the cost per kWh produced. And there is certainly room for improvement, because we could even hope to get down to just 36% SFRs for a fleet comprising hexagonal HCR LWRs and SFRs with a TBG of 0.25. This latter configuration appears to be the most efficient in terms of limiting the number of SFRs in the fleet.

5. Economic analysis: preliminary comments

Of course, this first trend is based solely on the consideration that an SFR is more expensive than an LWR and thus needs to be refined as not all SFRs or LWRs have the same economic performance levels.

For EPR, the following are the costs for France at a discount rate of 7%, as given in [6]:

Capital costs 59.98 USD/MWh = 55.8 €/MWh at $1 = €0.93

Operation and maintenance costs 13.33 USD/MWh = €12.4/MWh

Fuel, waste and carbon costs 9.33 USD/MWh = €8.7/MWh

There is no information for the 100% MOX EPR. Given that the costs of 30% MOX PWRs are substantially identical to those of UOX PWRs, the same values have been used, even though changing to 100% MOX does away with the need for zoning the MOX fuel assembly and only requires a single plutonium content, which simplifies fabrication.

Concerning SFRs, reference [7] indicates €1000/kg for reprocessing and €2000/kg for fuel fabrication. This leads to fuel cycle costs of €3.6/MWh for the self-sufficient SFR and €3.9/MWh for the breeder SFR taking into account additional blankets.

Lastly, we used the standard empirical formula for operational costs which assumes that the excess operational cost is half of the excess investment cost.

TABLE IV: Economics data for reactors

Cost of reactor series for SFRs and EPRs of the same power	1450 MWe self-sufficient SFR	1450 MWe breeder SFR	1450 MWe EPR with 100% MOX	1450 MWe EPR with 100% UOX
Investment + dismantling	72.5 (1.3* 55.8)	72.5 (1.3* 55.8)	55.8	55.8
Operation	14.3 (1.15*12.4)	14.3 (1.15*12.4)	12.4	12.4
Fuel cycle	3.6	3.9	8.7	8.7
Total cost (€/MWh)	90.4	90.7	76.9	76.9

Under these conditions, the following results were obtained for the F1 and F2 fleets:

TABLE V: Comparison between fleet F1 and F2

Fleet	Reactors in the fleet	Proportion of SFRs (%)	Cost of fleet (€/MWh)	Relative cost with F1 (%)
F1	SFR-000	100	90.4	100
F2	SFR-015, EPR-100	72	86.9	96

It can be seen that the excess cost of the F1 fleet compared with an UOX EPR fleet is 90.4 / 76.9 = 1.18, whereas that of the F2 fleet is only 86.9 / 76.9= 1.13. The integration of LWRs to form a fleet that does not use natural uranium makes it possible to lower its cost compared with that of a 100% self-sufficient fleet.

A key point worth underlining is that this fact can also be interpreted as a decrease in the excess investment cost of SFRs when they are used in a symbiotic fleet of SFRs and LWRs. It is simple to assess the effective investment cost for an SFR under these conditions: in the case of F2, the fleet cost is 86.9 i.e. that of a 100% SFR fleet with an investment cost, k, for an SFR so that k + 14.3 + 3.6 = 86.9. This indicates that k = 69.0 and thus the effective excess cost of an SFR in the F2 fleet is 69.0 / 55.8 = 1.24, which is lower than the value of 1.30 obtained when the investment costs of a LWR are compared directly with those of an SFR.

This can be explained by the fact that this SFR produces plutonium in excess, which has value, i.e. of being able to supply 100% MOX LWRs in plutonium which have an investment cost that is lower than that of SFRs. It is this additional service that makes it possible to compensate in part for the excess investment cost and to obtain a lower effective investment cost in the end. This effective investment cost depends, of course, on the way in which this plutonium is used by the fleet to which the SFR belongs.

This is the effective value that must be applied in studies focusing on the date from which SFRs become competitive, which brings forward the date as much as possible with respect to SFRs becoming competitive (if they are deployed in a symbiotic SFR + LWR fleet). The typical calculations based on the comparison of a LWR and an SFR presuppose (based on the simple excess investment cost) that these SFRs will be deployed in a 100% self-sufficient reactor fleet, which we have already seen is not the best solution from an economic perspective.

6. Economic analysis: database to be employed

Section 4 showed that it was possible to deploy a fleet that does not burn natural uranium when it has a limited number of SFRs, which does, in principle, move in the direction of reducing the kWh cost produced by the fleet. It nonetheless remains to be checked that the improved performance in terms of generation or consumption of plutonium has not been reached in return for prohibitive excess costs.

Case of SFRs

A standard SFR has a total breeding gain of 0.15 and using it in self-sufficient mode does not change the reactor but reduces the number of blankets, which results in a slightly lower fuel cycle cost. It was considered that optimisation was possible for the SFR-020 without any excess cost compared with the SFR-015. Going as far as a total breeding gain of 0.25 is only possible by adding a row of blankets and by increasing the size of the reactor vessel. An upper bound estimate of 2% had been given within the scope of transmutation studies [8]. This 2% estimate will be applied to the investment cost of SFR-025.

Case of the SFR fuel cycle

With respect to the fuel cycle cost, the cost of manufacturing uranium-depleted blankets can be disregarded (10 times cheaper than manufacturing an SFR fuel sub-assembly), but the cost of treating these blankets must be included since the cost of treating one blanket roughly amounts to the same as that for a fuel sub-assembly.

The fuel cycle cost applied in industrial-scale scenarios is that of an SFR, more specifically the SFR-015. The SFR-020 is considered to be an optimised version of the SFR-015 and does not, in principle, generate any excess fuel cycle costs. For the SFR-025, however, the idea is to go further (yet to be demonstrated) by adding a row of blankets, which would increase the number of blankets to treat by about 15%.

As the treatment part represents about 40% of the fuel cycle, the fuel cycle cost can be increased by 40% x 15% = 6% in the case of a total breeding gain of 0.25.

LWRs with high conversion ratios

The light water reactors with high conversion ratios (HCR) in this study were designed to be installed in an EPR vessel. Consequently, the excess investment cost should remain limited. The hexagonal version does not seem to raise any problems considering the fact that PWRs with hexagonal lattices already exist (VVER). We chose a value of 10% for the nuclear island alone, which accounts for 3 to 4% of the total investment. In the end, we chose 3% for the excess investment cost of the HCR light water reactors used in this study.

From a fuel cycle viewpoint, they are very similar to 100% MOX PWRs: no consumption of natural uranium, no need for separative work units (SWU), and similar plutonium contents. In terms of manufacturing fuel rods, about an extra third will have to be manufactured, even though the difference is less in terms of the number of pellets (a 100% MOX EPR fuel assembly is longer practically in the same proportion as that of HCR assemblies).

Under these conditions, the fuel cycle costs of the 100% MOX EPR were retained.

In the end, the economic database to be used can be described as follows:

TABLE VI: Economics data for reactors

Reactors	Investment	Operation	Fuel cycle
Sodium			
SFR-000	72.5	14.3	3.6
SFR-015	72.5	14.3	3.9
SFR-020	72.5	14.3	3.9
SFR-025	74.0	14.4	4.0
Water			
EPR-100	55.8	12.4	8.7
HCR-SQU	57.5	12.6	8.7
HCR-HEX	57.5	12.6	8.7

7. Results

The calculations were performed according to the database from the previous section. The following results were obtained:

TABLE VII: The economic performances of the fleet and the SFR effective excess investment costs

Fleet	Reactors in the fleet	Proportion of SFRs (%)	Fleet production cost (€/MWh)	Relative cost of the fleet compared with F1 (%)	Effective excess investment cost
F1	SFR-000	100.0	90.4	100	1.30
F2	SFR-015; EPR-100	72.2	86.9	96	1.24
F2a	SFR-020; EPR-100	66.1	86.0	95	1.22
F2b	SFR-025; EPR-100	60.9	86.3	95	1.23
F3a	SFR-015; HCR-SQU	65.8	86.6	96	1.23
F3b	SFR-015; HCR-HEX	47.9	84.5	93	1.19
F4	SFR-020; HCR-SQU	59.0	85.8	95	1.22
F4a	SFR-020; HCR-HEX	40.8	83.6	93	1.18
F4b	SFR-025; HCR-SQU	53.5	86.0	95	1.22
F4c	SFR-025; HCR-HEX	35.6	83.6	92	1.18

By comparing the two F2 fleets, it can be seen that the increase in the total breeding gain improves the situation, but only by a few percent. The SFR-025 makes it possible to reduce the cost of the fleet to 95% compared with F1 but this reduction was already at 96% with the

SFR-015. The costs of the F2b and F2a fleets are practically identical: the gain in the TBG is compensated by the excess investment cost.

No improvement was seen between the HCR light water reactor with a square lattice and the 100% MOX EPR: the improvement in the quantity of plutonium burned is neutralised by the estimated excess investment cost of 3% compared with the EPR. However, the HCR light water reactor with a hexagonal lattice makes it possible to improve performance since the cost of the fleet is reduced by 8% when coupled with the SFR-025, i.e. double that of F2 where the fleet cost is lowered by 4% compared with F1.

The effective excess investment cost falls within the 1.24 to 1.18 range, which is a marked improvement for the competitiveness of SFRs and reinforces the idea that they should be exploited in a combined SFR/ 100% MOX LWR fleet.

8. Sensitivity analysis: case of an increase in the SFR excess investment cost

If we chose to assume an excess investment cost of 50% instead of 30% for SFRs, the initial results would be:

TABLE VIII: Sensitivity to the SFR excess cost

		SFR/LWR excess cost 30%		SFR/LWR excess cost 50%	
Fleet	Reactors in the fleet	Fleet production cost (€/MWh)	Effective excess investment cost	Fleet production cost (€/MWh)	Effective excess investment cost
F1	SFR-000	90.4	1.30	102.8	1.50
F2	SFR-015; EPR-100	86.9	1.24	95.8	1.37
F2a	SFR-020; EPR-100	86.0	1.22	94.2	1.35
F2b	SFR-025; EPR-100	86.3	1.23	94.0	1.34
F3a	SFR-015; HCR-SQU	86.6	1.23	94.8	1.36
F3b	SFR-015; HCR-HEX	84.5	1.19	90.4	1.28
F4	SFR-020; HCR-SQU	85.8	1.22	93.1	1.33
F4a	SFR-020; HCR-HEX	83.6	1.18	88.7	1.25
F4b	SFR-025; HCR-SQU	86.0	1.22	92.8	1.32
F4c	SFR-025; HCR-HEX	83.6	1.18	88.1	1.24

According to this assumption, the effects are generally greater when the excess investment cost of SFRs is high, which is logical since it is even more profitable to build a 100% MOX LWR instead and to avoid investing in an SFR for the fleet. This is why the effective excess costs for the F4c fleet are only 18% and 24% respectively for the excess investment costs of 30% and 50%.

This shows that the higher the excess investment cost of an SFR, the more relevant it is to integrate this SFR into a well-adapted fleet since this reduces its initial handicap significantly.

9. Conclusion

The synergy between SFRs and LWRs provides a number of advantages from an economic perspective and it is highly probable that future nuclear fleets that no longer burn natural uranium will be composed of both breeder SFRs and HCR-type LWRs using 100% MOX fuels.

To lower the cost of the kWh generated by the fleet, it would be in our interest to have a maximum number of LWRs and a minimum of SFRs since the production cost of an SFR is higher than that of a LWR. As this fleet does not use natural uranium, the excess plutonium produced by the SFRs must be burned by LWRs, which has two significant effects:

- SFRs must provide the highest possible breeding ratio
- LWRs must burn the smallest possible amount of plutonium, which makes HCR LWRs an attractive solution.

These improvements in the production and consumption of plutonium will, of course, not be relevant if the costs required to reach these targets are too high.

By only taking into account reactors that very close to their technological maturity (SFRs with a TBG of 0.20 and EPR-type LWRs with 100% MOX), the kWh cost of the fleet can be decreased by 5% compared with that of a 100% SFR fleet.

The kWh cost of the fleet can be decreased by 8% compared with that of a 100% SFR fleet when we deploy slightly more efficient reactors requiring a slightly higher level of development, while remaining realistic since they can be operated in an EPR vessel (SFRs with a TBG of 0.25 and HCR-type LWRs with a conversion rate of 0.92).

In the very long term, even more efficient SFRs with carbide fuels or even metal fuels could further improve the situation.

This study has also shown that using SFRs in a mixed fleet rather than in a 100% SFR fleet makes the fleet more competitive .

In the case of a mixed breeder SFR/ 100% MOX LWR fleet, the SFRs produce plutonium which has a value that partially compensates for their excess investment cost. This economic value of plutonium is expressed through the possibility of being able to operate a certain number of LWRs with SFRs by supplying the LWRs with the required plutonium. As these LWRs have a lower investment cost than SFRs, it helps to lower the overall cost of the fleet.

Furthermore, the study has shown that it is possible to define an effective excess investment cost for SFRs, which depends on the fleet in which these SFRs are deployed.

This effect is relatively sensitive since the excess investment cost of 30% usually applied in LWR/SFR competitiveness analyses actually drops to about 20%. This has the impact of bringing forward the date from which SFRs are competitive by 10 to 20 years depending on the assumptions applied with respect to the uranium sources and the development of the global LWR fleet. In the case of an inherently higher excess cost, the use of SFRs in a mixed fleet would be even more relevant: when the excess cost of SFRs is set at 50% instead of 30%, their deployment in a mixed fleet brings this excess cost down to 24%.

Références

[1] D. Yun and al. Th/U-233 Multirecycle in PWRs ANL-FCRD-309

[2] T. Iwamura and al. Concept of innovative water reactor for flexible fuel cycle FLWR Nuclear Engineering and design volume 236, issues 14 16, August 2206 p ; 1599-1605 International conference on nuclear energy.

[3] M. Meyer, C. Coquelet-Pascal, R. Girieud, M. Tiphine, R. Eschbach, C. Chabert, CEA C. Garzenne, P. Barbrault, B. Gannaz, EDF R&D L. Van Den Durpel, D. Favet, M. Arslan, B. Carlier, M. Caron-Charles, J.C. Lefèvre, AREVA

Scenarios for minor actinides transmutation in the frame of the French Act for waste management

International Conference on Fast Reactors and related Fuel Cycles: Safe Technologies and Sustainable Scenarios March 2013

[4] P. Sciora et al., "A break even oxide fuel core for an innovative French sodium-cooled fast reactor : neutronic studies results", Global, Paris, Paper 9528 (2009)

[5] F. Damian et R. Lenain Réacteurs à eau à haut facteur de conversion RGN N°5 Septembre-Octobre 2010.

[6] OECD NEA Projected costs of Generating Electricity 2015

[7] I. Merino Rodriguez, F. Alvarez-Velarde, F. Martin-Fuertes Analysis of advanced european nuclear fuel cycle scenarios including transmutation and economical estimates 39th socieda Nuclear Espanola Meeting September 25-27 2013

[8] CEA : Sustainable radioactive waste management Act of June 28, 2006: results of research carried out on the separation and transmutation of long-lived radioactive elements, and on the development of a new generation of nuclear reactors .