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Assessment of the French nuclear energy system – A case study

Carlos E. Velasquez, Fidéllis B.G. L. e Estanislau, Antonella L. Costa, Claubia Pereira *

Departamento de Engenharia Nuclear, Universidade Federal de Minas Gerais, Av. Antonio Carlos, 6627 campus UFMG, 31.270-901, Belo Horizonte, MG, Brazil

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ABSTRACT

The country with the highest nuclear power contribution to its energy matrix is France with 72.28%. The French nuclear history reveals that they trust in reprocessing option since an early stage of the nuclear power plants. Therefore, this work is devoted to studying the two options of a fuel cycle, i.e., Open Fuel Cycle (OFC) and Closed Fuel Cycle (CFC) for this country and the economics of each scenario. The assessment begins using the MESSAGE, since the first official registration by the International Atomic Energy Agency (IAEA), which is in 1970 and tries to follow the model until 2016. After that, the MESSAGE adjusts the energy planning to fit best until 2034 remaining the nuclear activity in this country. The results show the best reactor option to supply 50000 MWyr until 2034 using the two fuel cycle models. Finally, it is shown the amount of resources needed to maintain the nuclear power industry in France and justify the French option of the fuel cycle based on the economic results. The results show the use of nuclear resources taking advantage of a closed fuel cycle. The idea is to show the sustainability of a closed fuel cycle, applying this methodology to countries in nuclear development with a different scenario.

1. Introduction

The French choice to develop nuclear energy began in 1948 with ZOE (EL-1) reactor, with nuclear power of 150 kW [1]. After that, France began to develop the nuclear industry through the Commissariat a l'Energie Atomique (CEA) [2]. Ten years later (1958), they began to invest in the reprocessing plant UP1 at Marcoule with the purpose to recover plutonium [3]. Nevertheless, they did not introduce the Mixed Oxide (MOX) technology in nuclear power reactors until the 1980s [4]. France has 58 power plants operational, 12 power plants permanently shutdown and 1 under construction [5].

The first eight nuclear reactors built in France were Gas Cooled Reactor (GCR) using natural uranium as a fuel. Also, there were one Heavy Water Gas-Cooled Reactor EL-4 (Monts D'ARREE), two Fast Breeder Reactor (FBR) -PHENIX and SUPER-PHENIX and one Pressurized Water Reactor (PWR) CHOOZ-A. All of them are already permanently shutdown. On the other hand, the operational reactors are 12 PWR-UOX (880–915 MWe), 22 PWR-MOX (890–915 MWe), 20 PWR-UOX (1300–1335 MWe) and 4 PWR-UOX (1495–1500 MWe) [6]. Fig. 1 shows the nuclear power plant locations as well as the reprocessing plants in France. The net nuclear electricity production in 2016 was 384000.00 GWh and the total electricity production (including nuclear) was 531300.00 GWh [5].

On the base year 2016, the French electricity matrix was supplied by 72.28% of nuclear energy. This technology is free of greenhouse gas emissions through the operation process. Since an early stage, French energy planning was based on the development of nuclear energy as the main source of energy. Nevertheless, France is a country with limited domestic uranium resources (80963 tU). To maintain its nuclear reactors working, it is needed between 8000 and 9000 tU per year [8,9]. Therefore, France must discover exploitable resources in other countries such as Canada, Kazakhstan, Namibia and Niger [9]. As a result, France in an early stage opted for a closed fuel cycle, recovering U and Pu, reusing their resources and exploring them the maximum achievable.

This work presents two scenarios simulated at MESSAGE [10]: one where the French option was an open fuel cycle (OFC) and another one with a closed fuel cycle (CFC), with recovering of U and Pu. It seeks to show the advantages of their current energy strategy against the opposite option. It would help to understand the importance of the applicability of reprocessing techniques taking advantage of nuclear resources. The chosen case study was France because it has limited uranium resources and a large fleet of reactors to feed. Therefore, it had to exploit its resources in the best possible way; thus, relying on a closed fuel cycle could extend the use of uranium at their maximum potential. Their nuclear strategy shows to the rest of the world the sustainability of nuclear power ahead of expectations.

* Corresponding author.
E-mail address: claubia@nuclear.ufmg.br (C. Pereira).

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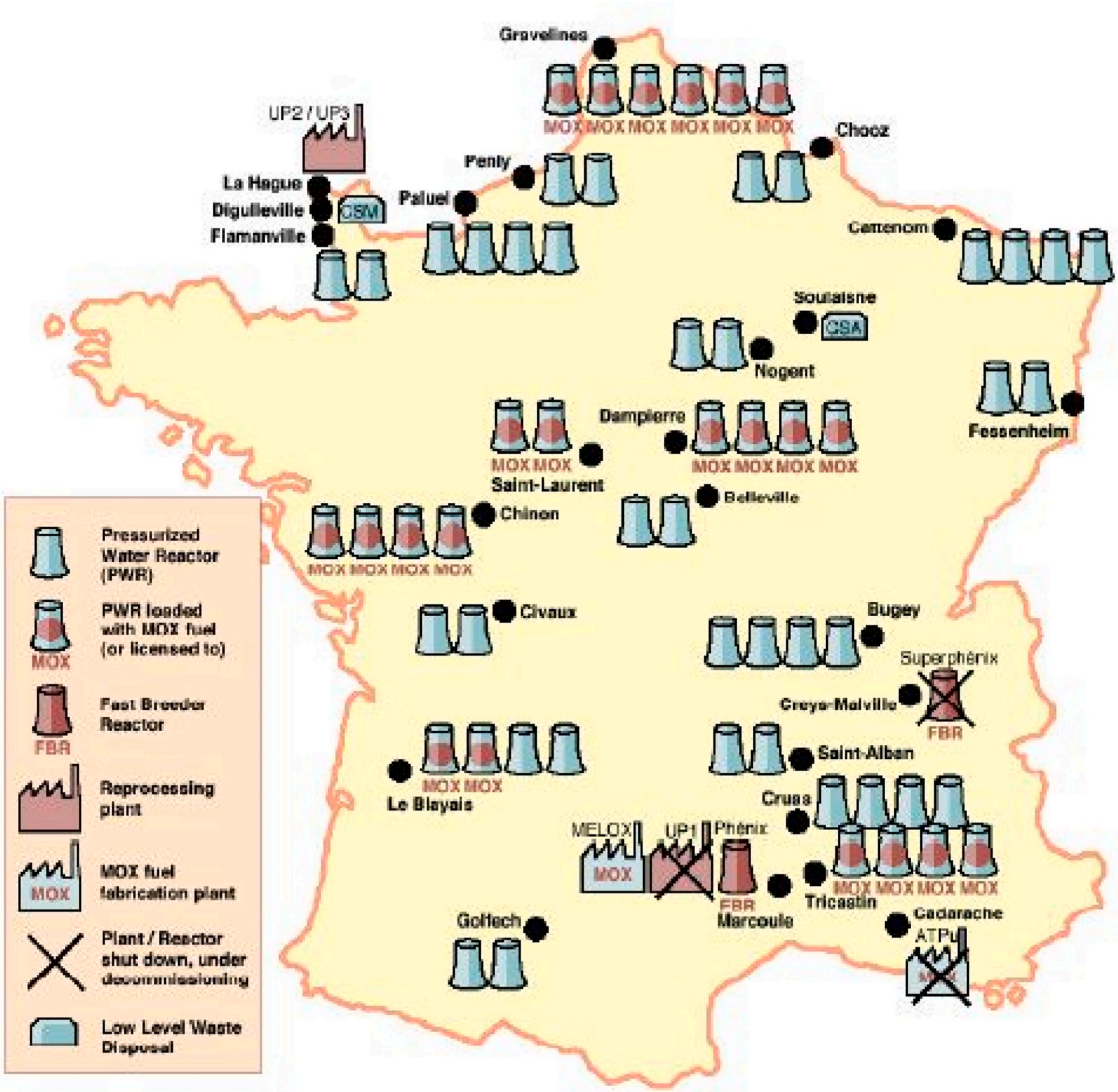

Fig. 1. Nuclear power and reprocessing plants in France [7].

Table 1
Main features of the PWR reactors modelled in Message.

Reactor	Electricity - total sum (TW.h)	Average Gross Capacity (MWe)	**Average Net Capacity (MWe)**	**Load Factor (%)**	**Burnup (GWd/tHM)**	Fuel Type
PWR-0	38.60	320.00	305.00	89.00	33.00	UOX
PWR-A	2366.62	940.83	901.67	95.00	36.26	UOX
PWR-B	4764.55	1372.20	1318.50	98.00	37.80	UOX
PWR-C	686.39	1560.50	1497.50	98.00	39.00	UOX
PWR-D	4415.94	950.18	906.82	92.2	35.14	UOX
MOX-PWR	4415.94	950.18	906.82	92.2	35.14	**MOX-UOX**

This work would show the importance of a closed fuel cycle. It presents the benefits of choosing an alternative path for the use of nuclear resources for countries with young nuclear development. Also, for countries with high nuclear power capacity, it shows the importance of reprocessing techniques for recycling and recovering the potential energy from the spent fuel.

2. Methodology

To develop the French nuclear energy system in MESSAGE, all the features of reactors working since 1970 to 2016 were obtained from PRIS-IAEA [5] as well as the domestic uranium reserves. As mentioned before, France has 58 operational PWR reactors, and 1 PWR already permanent shutdown. Therefore, the best representation of the French scenario was classifying their reactor in five different types of PWR (Table 1) according to an average of energy capacity and type of fuel used. The classification corresponds to the following description:

1. PWR-0 corresponds to the CHOOZ-A (ARDENNES);
2. PWR-A corresponds to an average of the BLAYAIS-(3, 4), BUGEY-(2, 3, 4, 5), CRUAS-(1, 2, 3, 4), FESSENHEIM-(1, 2);

Table 2
Main features of the GCR and FBR reactors modelled in MESSAGE.

Reactor	Electricity – total sum (TW.h)	Average Gross Capacity (MWe)	**Average Net Capacity (MWe)**	**Load Factor (%)**	**Burnup (GWd/tHM)**	Fuel Type
GCR	223.62	555	540	75.00	5.00	UOX-NatU
FBR	27.83	692	665	24.2	66.00	PuO2+UO2

Table 3
Availability of French domestic and non-domestic uranium resources [8,10].

Price	$40/kgU	$45/kgU	$50/kgU	$55/kgU	$60/kgU	$65/kgU
National Uranium (tonne)	14530.17	18030.17	18030.17	6606.167	7350.167	16416.17
Price	$70/kgU	$80/kgU				
International Uranium (tonne)	22000	Unlimited				

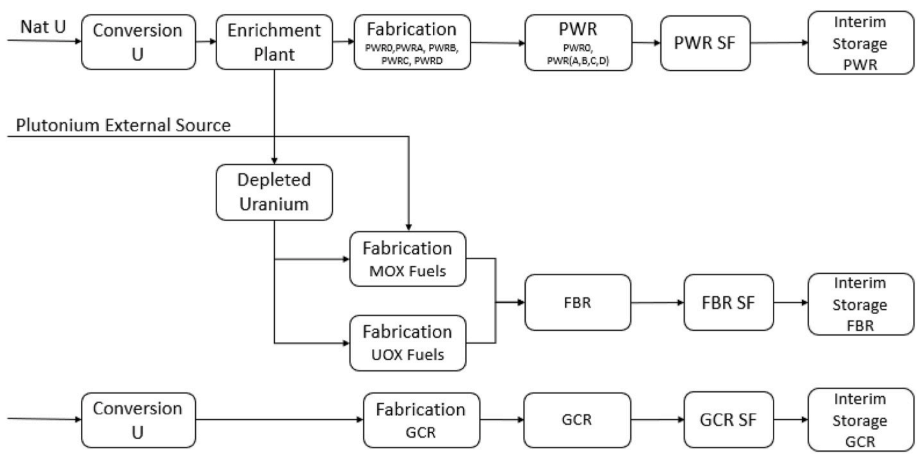

Fig. 2. Scheme of the open nuclear fuel cycle.

3. PWR-B corresponds to an average of the BELLEVILLE-(1, 2), CATTENOM (1, 2, 3, 4), FLAMANVILLE-(1, 2); GOLFECH-(1, 2), NOGENT-(1, 2), PALUEL (1, 2, 3, 4), PENLY-(1, 2), ST. ALBAN-(1, 2);
4. PWR-C corresponds to an average of the CHOOZ (B-1, B-2), CIVAUX-(1,2)
5. MOX-PWR corresponds to an average of the BLAYAIS-(1,2), CHINON (B-1, B-2, B-3, B-4), DAMPIERRE-(1, 2, 3, 4), GRAVELINES-(1, 2, 3, 4, 5, 6), ST LAURENT (B-1, B-2), TRICASTIN (1, 2, 3, 4)

Table 2 shows the features of the reactors. The 8 GCR and 1 HWGCR were summarized to 1 GCR using natural uranium as fuel. The PHENIX and SUPERPHENIX were also summarized to 1 FBR using depleted uranium and (PuO_2+UO_2). The relevance to simulate the GCR and the FBR is because they represent an important utilization of uranium resources, which are limited for France. That is:

1. GCR corresponds to an average of the BUGEY-1, CHINON (A-1, A-2, A-3), EL-4 (MONTS D'ARREE), G-(2,3) MARCOULLE, ST LAURENT (A-1, A-2)
2. FBR corresponds to an average of the PHENIX and SUPER-PHENIX reactors.

Table 3 shows the primary energy classified in domestic uranium and international uranium. On the one hand, the domestic resource has a total amount of 80963 tU in a price range from $40/kgU to $65/kgU. On the other hand, the international uranium classified has two prices: one at $70/kgU with 22000 tU; and unlimited uranium at $80/kgU. The prices are different to distinguish the evolution of the domestic from the international resources needed to supply nuclear power plant (NPP) demand. The international uranium price was chosen to be higher than the domestic price allowing the consume of the domestic reserves in the first place. The 22000 tU at $70/kgU is intentionally different from the unlimited resource to have a better visualization of the optimization

Table 4
Analytical mass flow for the open fuel cycle.

Output Parameters	Annual Fresh Fuel (FF)	Fuel In Core	Natural Uranium (Nat U)	Conversion (Cn)	Separative Work Unit (SWU)	Depleted Uranium (DepU)	Spent Fuel Discharged (SFD)
Reactor	tHM	tHM	tHM	tHM	tSWU	tHM	tHM + tFP
GCR	105.59	183.21	105.59	105.59	–	–	105.59
PWR-0	10.03	32.64	90.23	90.23	52.91	52.91	10.03
PWRA	25.16	113.01	207.98	207.98	118.52	182.82	25.16
PWRB	36.45	142.62	288.02	288.02	161.51	251.56	36.45
PWRC	40.22	123.14	303.12	303.12	167.03	262.45	40.22
PWRD	27.55	87.01	227.71	227.71	129.76	200.16	27.55

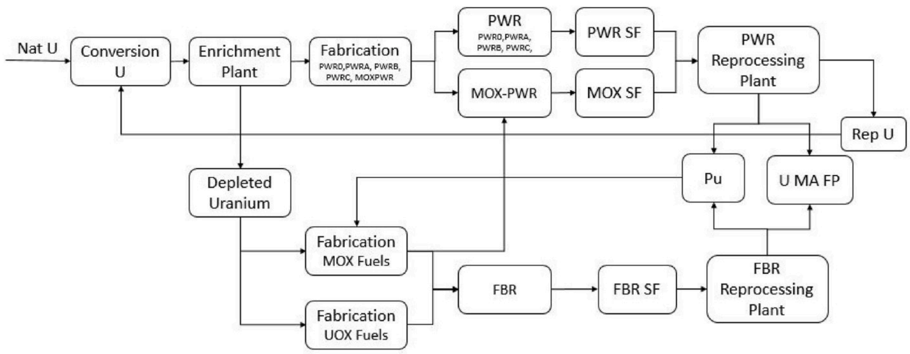

Fig. 3. Scheme of the closed nuclear fuel cycle.

Table 5
Analytical mass flow for the closed fuel cycle.

Output parameters	Symbol (Unit)	MOX-PWR	Output parameters	Symbol (Unit)	FBR
Fresh Fuel UOX	FFUOX (tHM)	18.36	**Fresh Fuel MOX**	FFMOX (tHM)	9.20
Fuel in Core UOX	Fuel In Core UOX (tHM)	58.00	**Fresh fuel axial blanket**	FFAx (tHM)	4.02
Fresh Fuel MOX	FFMOX (tHM)	9.18	**Fresh fuel radial blanket**	FFRad (tHM)	3.88
Fuel in Core MOX	Fuel In Core MOX	29.00	**Spent fuel discharged**	SFD (tHM + tFP)	17.09
Natural Uranium	Fuel In Core MOX (tHM)	151.80	**Reprocessed plutonium used**	RepPuUsed (tHM)	1.84
Conversion	Cn (tHM)	151.80	**Spent fuel reprocessing**	SFR (tHM)	15.59
Separative Work	SWU (tSWU)	86.51	**Reprocessed Plutonium**	RepPu (tHM)	1.84
Depleted uranium	DepU (tHM)	133.44	**Plutonium losses**	LosPu (tHM)	0.01
Spent fuel UOX discharge	SDUOX (tHM + FP)	18.36	**Minor actinides**	RepMA (tHM)	0.04
Spent fuel MOX discharge	SDMOX (tHM + FP)	9.18	**Fission Products**	RepFP (t)	0.60

results when using international uranium resources. The unlimited uranium resource at $80/kgU was chosen according to IAEA resource category, which is the second-lowest classification of uranium price. For the OFC case, it was used plutonium just for FBR. This plutonium comes from an external source, which uses the Pu resources at $5840 per gram [11].

Fig. 2 shows the once-through fuel cycle scheme. The only plutonium used is for the FBR, which is important to consider knowing the uranium expenses needed to supply this kind of reactor due to the small domestic resource. The open fuel cycle considers the plutonium acquisition in the market at $5840000/kgPu. Table 4 presents the mass flow for the reactors on the OFC used for the modelling. Whereas Fig. 3 shows the closed fuel cycle scheme which considers recycling of U and Pu from the PWR (A, B, C, MOX) spent fuel. Table 5 presents the mass flow of the MOX for the PWR-MOX and the FBR.

Tables 6 and 7 present the technical and economic features used at MESSAGE for the six modelled reactors, respectively. The technical features of the reactors are presented in Table 6, which most of them were used in the OFC and CFC. The main difference between the OFC and CFC is the use of the PWR-MOX, which uses reprocessed uranium and plutonium, in the CFC. In the OFC an exception was made using plutonium for the FBR reactor, which represents two experimental reactors, Phenix and Super-Phenix. The economical characteristics followed as presented in MESSAGE [10]. The scenarios simulation includes the mass flow from the primary energy (uranium ore) to the delivered energy (electricity) to accomplish the French electricity demand. The demand is shown in Fig. 4, which already contains the electricity demand between 1970 and 2016. After that, from 2017 to 2034, the MESSAGE uses the optimization to satisfy a constant demand of 50000

Table 7
Economical characteristics of the reactors [10].

ITEM	Unit	All PWR including (MOX-PWR)	GCR	FBR
Investment Cost	US $/kW(e)	3000	3500	3500
Fixed O&M Cost	US $/kW/yr	50	55	55
Variable O&M Cost	US $/kW.yr	10	15	50
Lifetime	Yr	40	60	–
Construction Time	Yr	5	5	5
Enrichment	US $/kg SWU	110	–	–
Fuel Fabrication	US $/kg HM	275	65	1500
Reprocessing	US $/kg HM	600	–	1500

Table 6
Technical features of the reactors [5,6,10,12].

Item	Symbol	Unit	PWR-0	PWR-A	PWR-B	PWR-C	**PWR-D or PWR-MOX**	GCR	FBR
Nuclear Capacity	NC	GW(e)	0.305	0.915	1.335	1.500	0.915	0.540	0.665
Load Factor	Lf	–	0.92	0.89	0.98	0.98	0.95	0.57	0.24
Thermal Efficiency	Eff	–	0.31	0.33	0.35	0.34	0.33	0.29	0.42
Discharged Burnup	Bu	GW.d/tHM	33.00	36.27	37.80	39.00	35.14	5.37	66/4.8/4.2
Residence Time	Tr	EFPD	1095.00	1460.00	1399.25	1095.00	1460.00	992.44	121/121/141
Enrichment	Enr	–	0.040	0.037	0.035	0.034	0.037/0.09(Pu)	Nat-U	–
Tail Assay	Ta	–	0.003	0.003	0.003	0.003	0.003	–	0.003
Cooling Time	Tcool	yr	5	5	5	5	5	5	2

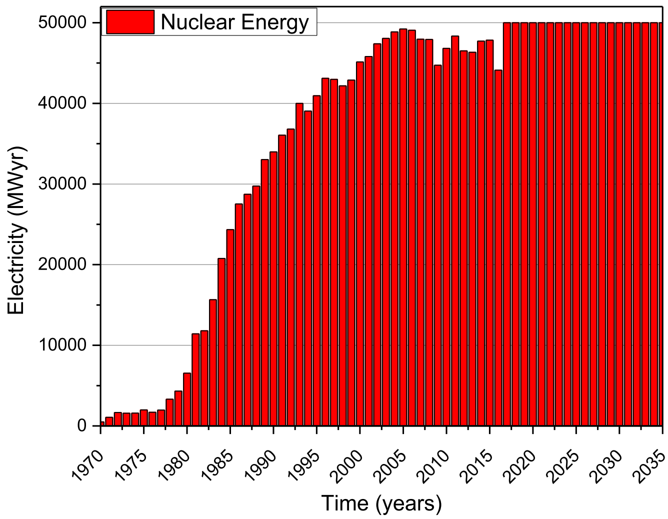

Fig. 4. French electricity demand by nuclear energy [10].

MWyr. Therefore, it would be possible to choose between the four PWR reactors to supply the electricity required until 2035. There is no lifetime for the FBR because the Phenix and Super-Phenix were prototype reactors; therefore, they did not have a specific lifetime.

3. Results

Each reactor has a specific power supplied until 2016, after that the MESSAGE optimized the results to obtain the demand of 50000 MWyr. Fig. 5 presents two scenarios, an open fuel cycle and a closed fuel cycle. On the one hand, for the OFC the optimization deploys the PWR-C over all the other PWR (A, B, D) options. The model choice was due to the high energy production of the PWR-C, and because the nuclear fuel cycle needs less enriched uranium to produce a higher amount of energy compared to the other PWR technology. On the other hand, the CFC optimization chooses to deploy the PWR-A as a priority from 6745 MWyr in 2016–27864 MWyr in 2035. Then, the PWR-MOX has a small increase from 14046 MWyr in 2016–14589 MWyr in 2035. This optimization can be explained due to the utilization of the closed fuel cycle is much cheaper for the long term than the uranium enrichment. Therefore, the optimization chooses to reduce the amount of enriched uranium and continue recycling and reprocessing spent fuel.

Fig. 6 shows the difference in the total operation and maintenance (O&M) costs for the OFC and CFC. This includes the fixed (Fix) and variable (Var) costs for each cycle. The CFC option is a little bit more expensive than the OFC in terms of fix costs because in the CFC is used more reactors PWR-A and MOX-PWR to meet the demand (50000 MWyr). In contrast, the OFC uses more PWR-C with the highest power to meet the demand. The main differences between them are due to the reactor option in each cycle, as can be seen in Fig. 7. The sum of the O&M cost for the PWR-A and PWR-MOX options in the CFC is a little more expensive. Nonetheless, these differences could be compensated by the nuclear fuel cycle from the natural uranium price to the reprocessing and storage.

The CFC option is much cheaper than the OFC in terms of nuclear fuel cycle costs, as shown in Fig. 8. The fuel cycle includes the primary energy, the energy conversion, the separative work unit, delivered energy and the spent fuel storage. An early choice of a CFC reduces the fuel cycle prices. There are two great differences between both cycles: the first one is that the OFC needs more amount of natural uranium, which increases the demand for this resource. The second is that the expenses of the uranium enrichment are higher than using a closed fuel cycle recycling uranium and plutonium, which turns the CFC much more competitive concerning the fuel costs. The CFC must enrich a lower amount of uranium than the OFC. It also needs fewer uranium resources

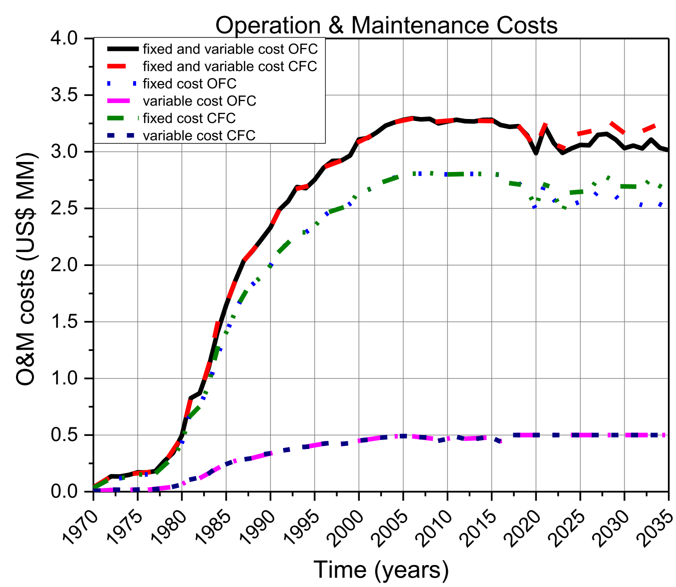

Fig. 6. O&M costs for the OFC and CFC.

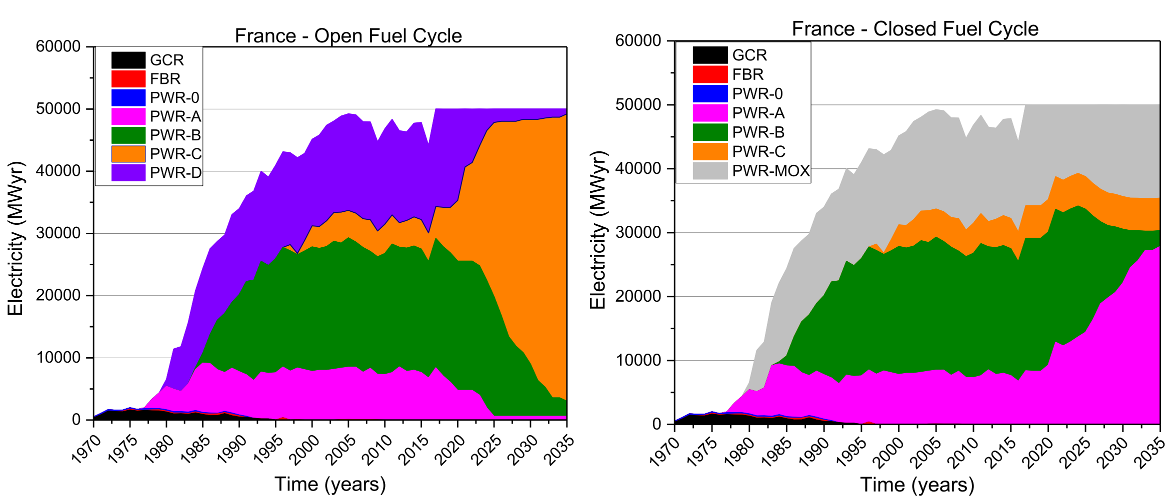

Fig. 5. French electricity demand model for each reactor left (open fuel cycle) and right (closed fuel cycle).

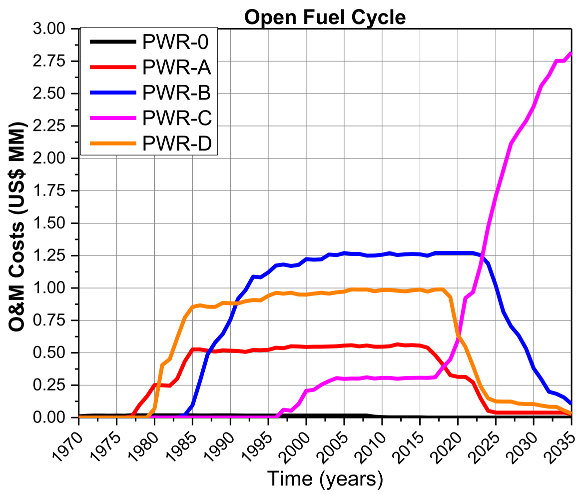

Fig. 7. Differences in O&M by reactor.

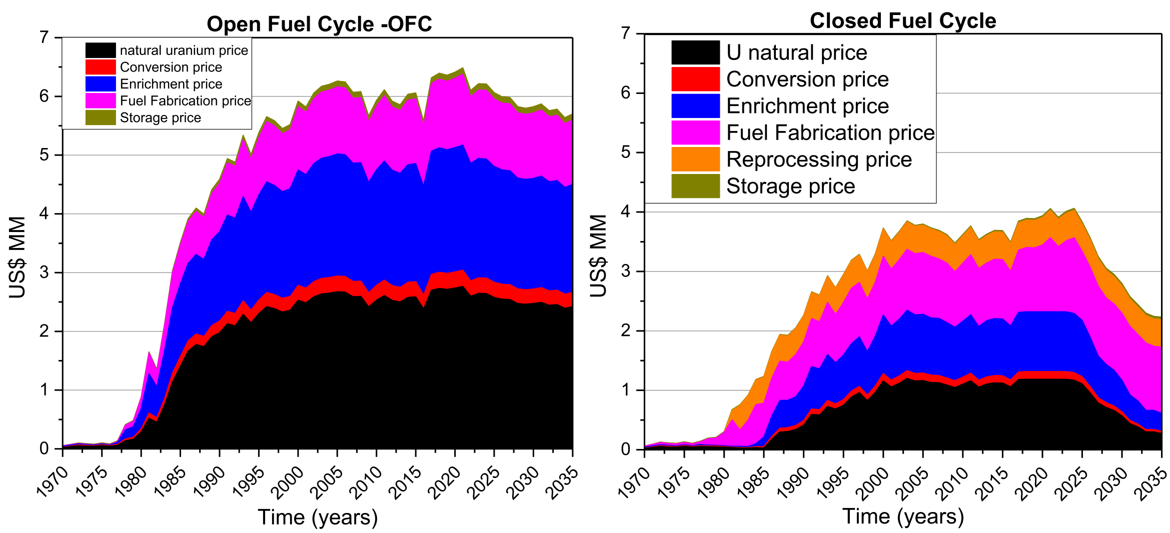

Fig. 8. Fuel cycle costs for CFC and OFC.

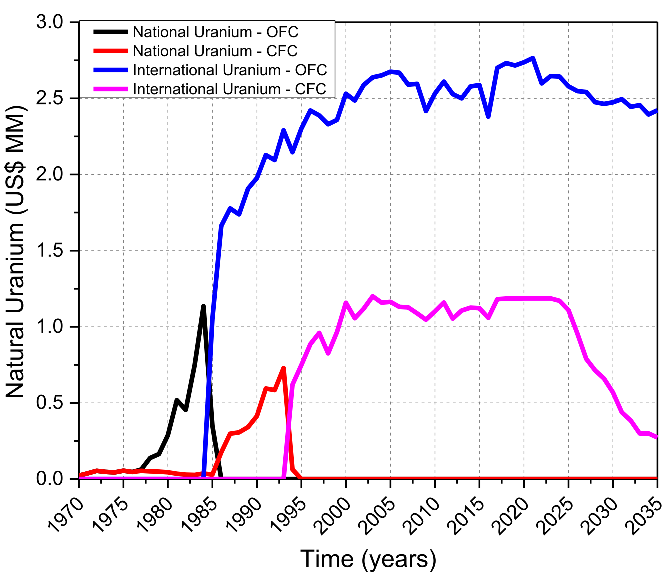

Fig. 9. National and International uranium resources.

due to uranium recycling and the utilization of plutonium, which is an important factor for increasing the installed capacity of PWR-MOX.

The fuel cycle costs based on the uranium ore exploration were already classified in Table 3. Figs. 9 and 10 show the evolution of the domestic resources which is 80963 tU and for the first international price at $70/kgU is 2200 tU. Thus, for the OFC the natural uranium ends up in 1985, while for the CFC reserves finished in 1994. Therefore, the CFC option uses natural uranium 9 years ahead than the OFC due to the plutonium and uranium recycling. This shows the importance of a CFC in a country with limited resources. Whereas, the international uranium limited to 22000 tU at $70/kgU finished in 1986 for the OFC, in the CFC it ended in 1996. After that, the program begins to use natural uranium with an unlimited resource at $80/kgU. Therefore, to maintain the nuclear reactor working until the year 2035 the OFC needs around 1620688 tU, while the CFC needs around 582868 tU. Hence, the OFC cycle requires around 2.78 times more than the CFC to supply its reactor until 2035.

Fig. 11 shows the installed capacity for each nuclear fuel cycle. Despite the GCR has an installed capacity until 2030 due to the lifetime of the reactors defined as 60 years, they stop working on 1994. Therefore, it does not interfere with the model but still has an installed capacity remaining. Besides, the model considers that the GCR begins its

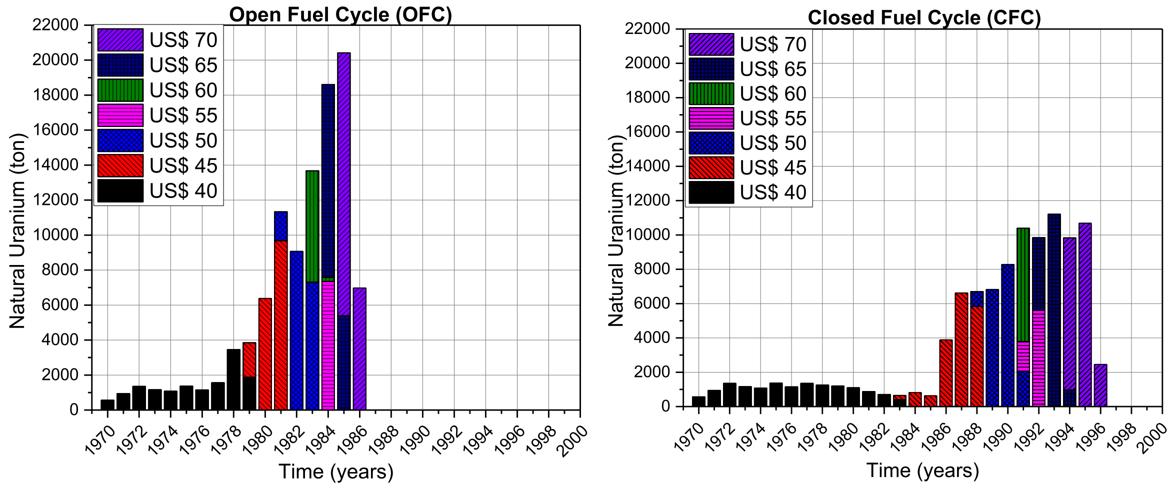

Fig. 10. Evolution of the national natural Uranium price for the OFC and CFC.

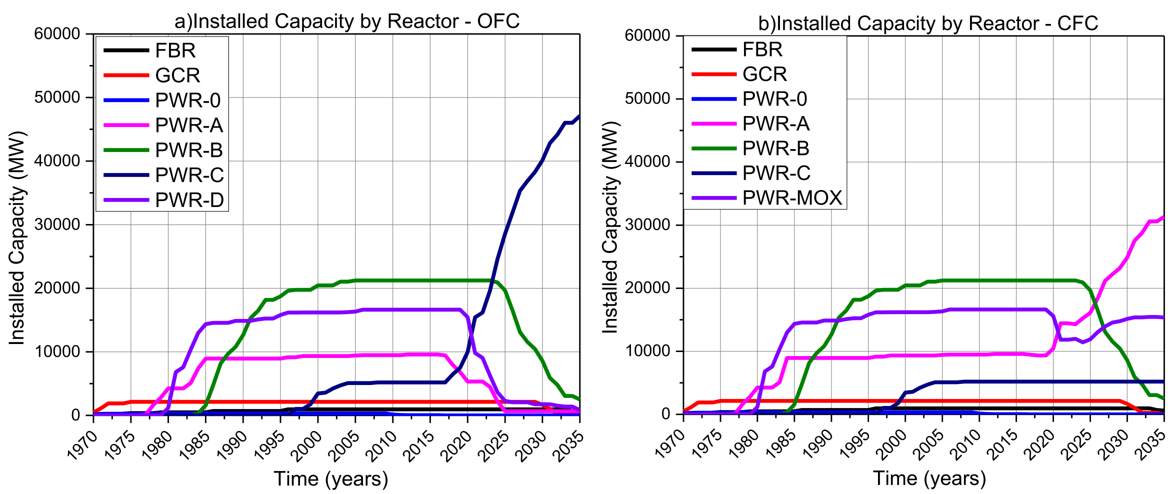

Fig. 11. Installed Capacity by NPP for the a) OFC and b) CFC.

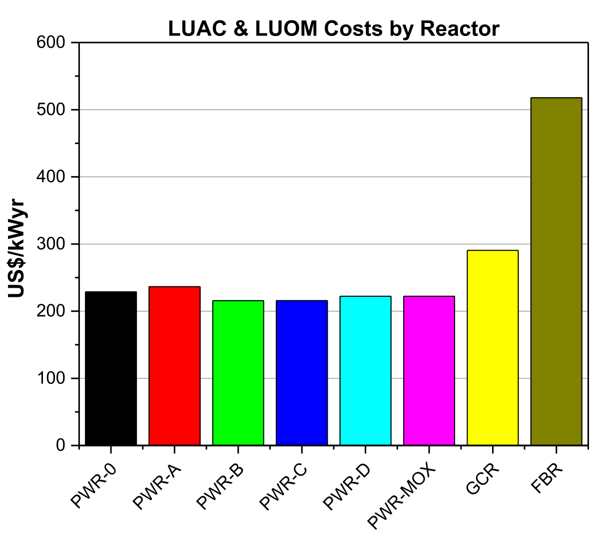

Fig. 12. LUAC&LUOM costs by reactor.

operation since 1970. Nonetheless, France decided to shutdown six of them due to economic reasons and two of them due to technical reasons (graphite expansion, steel embrittlement) [13]. Fig. 12 shows the levelized unit lifecycle amortization cost (LUAC) and the levelized unit lifecycle operation and maintenance cost (LUOM) for all the reactors studied in this case study. The FBR has the highest value and is expensive compared to other reactors. The FBR reactors also have installed capacity capable to supply energy for a long time but both of them were shutdown due to the end of the proposed tests (prototypes) [14]. The PWR-0 representing the CHOOZ-A, which represents the first PWR built in France, was shutdown after 24 years due to perform an examination program to have complete feedback of the vessel irradiation [15]. The PWR-A is a little more expensive than the others but has the advantage to use a lower amount of enriched uranium, which becomes an advantage in the CFC. Thus, the CFC opted to install the PWR-A reactors to accomplish the demand by increasing the installed capacity from 9440.63 MW in 2016–31307.19 MW in 2035, while the OFC drops from 9587.44 MW to 655 MW in 2035. On the other hand, the PWR-D, which replaces the PWR-MOX in the OFC, drops from 14046 MWyr in 2016 to 790 MWyr in 2035; while in the CFC, the PWR-MOX goes from 14046 MWyr in 2016–14589 MWyr in 2035. In contrast, the OFC deploys the PWR-C which needs less enriched uranium to produce higher amounts of electricity than the other PWRs. The PWR-C in the OFC goes from 4618 MWyr in 2016–46172 MWyr in 2035, while in the CFC it goes from

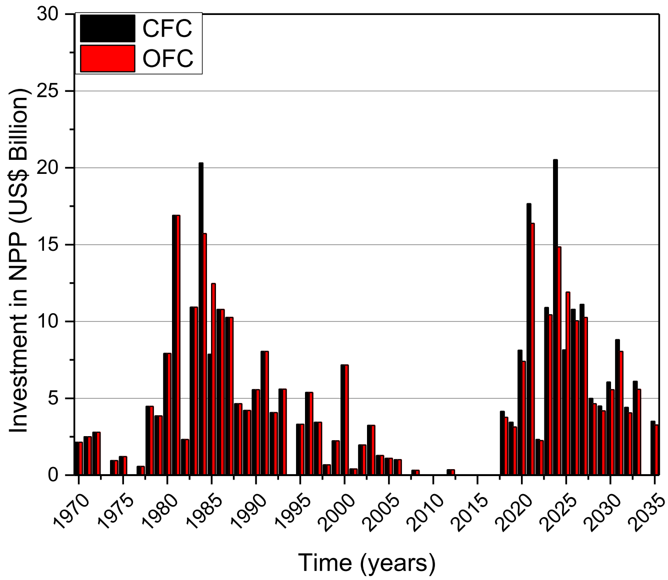

Fig. 13. Investment costs in NPP.

4618 MWyr in 2016–5092 MWyr, representing the installation capacity of just one nuclear reactor.

Finally, Fig. 13 shows the investments in NPP until 2034. The CFC invests in NPP are around $295 billion, while the CFC investments in NPP are around $305 billion. The difference is approximately $9.78 billion, which is easily recovered by recycling uranium and plutonium in a CFC.

4. Conclusions

This work tries to represent the French scenario as an example of energy planning development based on nuclear energy. The French option to introduce an early closed fuel cycle saves up millions of tons of uranium. It is evident that France needed of natural uranium exploration from other countries to remain their reactors operational. The CFC opted for the use of PWR-A due to the lower needs of enriched uranium, which has an economic impact on energy planning. Besides, the investment costs are a little bit higher, in the CFC, but it is compensated by recycling and reprocessing U and Pu. On the other hand, the OFC option was to install nuclear power plants with higher electricity capacities to supply the demand. The choice of CFC could increase by 42% the usage of uranium more than OFC. The development of their reprocessing plants saves up highly amount of money, which was eventually recovered by using their own installed reprocessing plants instead of acquiring plutonium and uranium. As well as the CFC saves up the expenses of acquired more amount of uranium ore due to uranium recycling by its technology.

France's nuclear energy system should be taken as an example for all countries with nuclear power capacity installed. Their nuclear energy system shows that, if opted for the CFC, the utilization of uranium resources could be extended significantly, in contrast to the once-through cycle. Even, recycling of plutonium could be useful for future uses in thorium-based reactors, due to thorium's abundance in the earth's crust.

Further works will apply this methodology including new reactor technologies (HWR, ALWR, FBR) into the Brazilian nuclear energy planning and other countries with a nuclear capacity installed.

CrediT author statement

Carlos E. Velasquez, Fidéllis B. G. L. e Estanislau, Antonella L. Costa and Claubia Pereira: ConceptualizationMethodology; Carlos E. Velasquez, Fidéllis B. G. L. e Estanislau: SoftwareValidation.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2020.100513.

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