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A proper spent nuclear fuel management strategy could enhance the continuity of nuclear power in the Spanish energy mix

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Summary

This article presents two economic analyses performed with the Mariño model, which was specially designed to analyse the costs of different spent nuclear fuel (SNF) management strategies in the real Spanish context. These analyses are: (a) a Monte Carlo study for those strategies and (b) the effects of a longer operational lifetime for the Spanish nuclear power plants (NPPs) on the costs of spent nuclear fuel (SNF) management. For the first analysis, a triangular distribution for the different unitary costs was assumed and the data and assumptions from numerous studies were used to obtain the values required for the distribution. The second analysis was performed for the current official shutdown dates for the NPPs, and the results were compared to other operational lifetime scenarios. The main assumption for these scenarios was a progressive shutdown of the reactors, in order to avoid numerous shutdowns in a few years. These scenarios were proposed for 40 to 60 years of mean operational lifetime of the reactors. The results show that, for all scenarios analysed, the additional electricity production due to longer operational lifetimes compensate the extra costs caused by the larger amount of SNF to be managed. Additionally, for the current SNF management strategy, a progressive shutdown at 40 years of mean operational lifetime has shown to entail lower costs than the official shutdown scenario. However, a strategy without a centralised interim storage facility would be the most economically favourable one for all the scenarios analysed.

KEYWORDS

centralised interim storage, direct disposal, reprocessing, Spain, spent nuclear fuel, spent nuclear fuel management

1 | INTRODUCTION

The economics of the nuclear fuel cycle have been a focus of attention of numerous studies over the years. For this purpose, different number of economic models have been developed, where a set of characteristics change from one model to another in order to make them simpler, more efficient or more accurate. Overall, these models can be classified according to the material flows calculation method, to the probabilistic approach, to the methodology of the cost calculation or to the overall scope of the model.

Firstly, according to the material flows, models can be classified into equilibrium or dynamic models.[1] On the one hand, equilibrium models analyse a fixed image of the material flows, at a moment of stability of the nuclear fuel cycle, in a static status. They are easy to analyse and implement, which is why they have been thoroughly used internationally, such as by the OCDE,[2] Kim et al.[3] among others shown in Table 1. On the other hand, dynamic models vary the material flows over time, as well as the costs associated to the nuclear fuel cycle. Thus, these types of models add more complexity than the equilibrium models, but they also add more accuracy to the final cost estimation, which is why they are also highly common in international studies, such as by De Roo and Parsons[9,10] or Chen et al.[25]

Secondly, according to the probabilistic approach, international models can be classified into deterministic and stochastic models.[1] The former models obtain the costs using the best estimation of the unitary costs involved in the nuclear fuel cycle in order to obtain the "most likely" cost for each strategy considered in the analysis, which may be affected by subjectivity. However, the results of these models are usually submitted to sensitivity analyses

TABLE 1 International models summary

	Material flows		Probability		Scope		
Study	Equilibrium	Dynamic	Determ.	Stoch.	Gen.	Part.	Costs
OCDE 1994[4]	X		X		X		NPV/E
Charpin et al.[5]	X		X			France	NPV
Harvard 2003[6]	X		X		X		LCOE
BCG 2006[7]	X		X		X		NPV
Ramana and Suchitra[8]	X		X			India	NPV
De Roo and Parsons[9, 10]		X	X		X		LCOE
Park et al.[11]	X		X			Korea	N/A
Ko and Gao[12]	X		X	X		Korea	NPV/E
Recktenwald and Deinert[13]	X		X	X		USA	NPV
OCDE 2013[2]	X		X		X		LCOE
Brinton and Kazimi[14]		X	X		X	USA	NPV
Zhou et al.[15]	X		X		X		NPV/E
Kim et al.[1]	X			X	X		NPV
Kim et al.[16]		X		X		Korea	LFCC
Gao et al.[17]		X	X			China	LCOE
Ganda et al.[18]	X			X	X		LCAE
Zhang et al.[19]	X		X	X		China	LCOE
Choi et al.[20]		X	X		X		N/A
Kim et al.[3]	X		X			Corea	CAP
Kim et al.[21]		X		X	X		N/A
Gao et al.[22]		X	X			China	LCOE
Zhang et al.[23]		X	X			China	LCOE
Yue et al.[24]	X		X			China	LCOE
Chen et al.[25]		X	X			China	N/A
Krasnorutskyy and Kirsanova[26]	X		X			Ucrania	LC

so as to help mitigate these possible biases. The latter models consider the uncertainty of the different unitary costs, due to the lack of experience or data, the confidentiality of the data, the effect of scale, etc. Thus, they use probability distributions instead of a best estimate value.

Thirdly, the models can use different methods to calculate the costs, but the two most frequently used are the Net Present Value (NPV) and the Levelized Cost of Electricity (LCOE). Sometimes, in order to levelize the costs, the NPV is divided among the total electricity production estimated, such as in the studies performed by Ko and Gao[12] or Zhou et al.[15]

Finally, the scope or the context of these models can vary. Most of them are developed to estimate the costs of the nuclear fuel cycle of a new nuclear power plant, or nuclear fleet, and the context is generic, in order to be able to implement the model in different countries, as seen in Table 1. However, other models consider a more particular context, in order to obtain more accurate results for a specific country, which is the main focus in those studies.

In Spain, there is a very particular context, since there has been a delay of a decade in the construction of a centralised interim storage (CIS) facility, which had been planned to be constructed in 2010 in the sixth General Radioactive Waste Plan of 2006. Due to this delay, several Independent Spent Fuel Storage Installations have been required caused by the lack of capacity of the spent nuclear fuel (SNF) pools, thus, significantly changing the original plan and the associated costs.

As can be concluded from Table 1, which shows a review and a classification of numerous international models, there are no economic models that analyse this particular situation in Spain. Therefore, in order to obtain more accurate results for the Spanish SNF scenario, the Mariño model was developed, which was firstly introduced in Rodriguez-Penalonga.[27] In this study, a deterministic analysis was performed in order to help determine which back-end strategy had the lowest costs considering the current Spanish context, where a sensitivity analysis was included.

Nevertheless, these analyses could be expanded and the model could be used to obtain more results about the Spanish SNF scenario that may favour the continuity of nuclear power in the Spanish energy mix. This is a key issue, because nuclear energy plays an important role in the Spanish energy mix for several reasons: it reduces the energy dependence and has a greater security of supply in comparison to fossil fuels, it has zero direct greenhouse gas emissions, provides stability to the electricity grid and, in the last decade, it has been producing around 20% of the electricity demand in Spain, as shown in Figure 1.[1] Therefore, nuclear energy could be a great asset for Spain in the energy transition, as it would help reducing GHG emissions, mitigating climate change and maintaining the stability of the electricity tariff prizes and of the electricity grid.

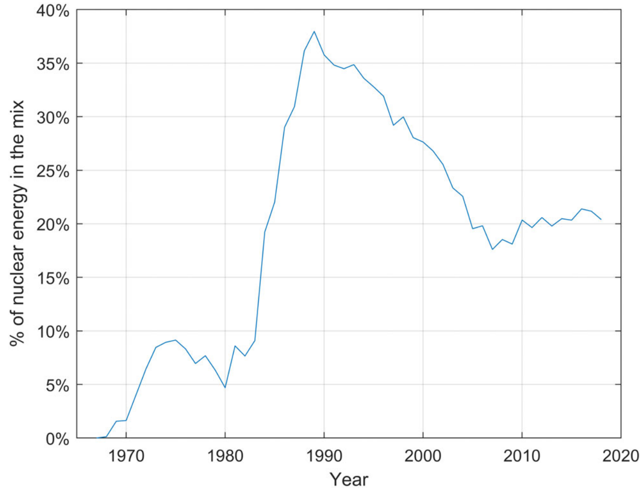

FIGURE 1 Percentage of nuclear power production over the total electricity production in Spain [Colour figure can be viewed at wileyonlinelibrary.com]

Due to the advantages explained above, it might be interesting to consider the continuation of NPPs in the Spanish energy mix because nuclear power plants are already operating in Spain and, regardless of the final inventory of SNF, some nuclear emplacements will have to be constructed, such as a Deep Geological Repository (DGR). Additionally, other emplacements, such as independent spent fuel storage installations (ISFSIs), have already been constructed due to the current inventory of nearly 5000 tHM of spent nuclear fuel (SNF) that needs to be managed. Therefore, the two main purposes of this article are: (a) to further deepen into the analysis performed in Rodríguez-Penalonga,[27] by means of a Monte Carlo simulation with the model, in order to better understand the economics of the back-end strategies in Spain and (b) to analyse the effects of the nuclear power plants (NPPs) operational lifetime in the total and levelized costs of SNF management in order to determine whether the benefits of continuing nuclear power production can compensate the cost increment of SNF management in Spain.

2 | THE MARIÑO MODEL

The methodology used in this article to calculate the costs of the back-end strategies of the nuclear fuel cycle is the Mariño model, which is fully described in Rodriguez-Penalonga.[27] This model was designed for the particular Spanish SNF management context. Due to the particularities of a specific country and a real scenario as opposed to a hypothetical situation, more flexibility is required. Thus, instead of using the LCOE, the costs are calculated with the Net Present Value (NPV), which is then divided by the estimated electricity production of the NPPs throughout their life cycle in order to levelize the costs in mill/kWh. Table 2 summarizes the Spanish real scenario.

The Mariño model analyses the costs for three different scenarios, one of them with two variations. Scenario 1 considers the update to 2017 of the strategy established in the VI General Plan for Nuclear Waste of 2006: a direct disposal strategy with a centralised interim storage (CIS) facility with re-encapsulation, where the casks are metal dual-purpose casks. Scenario 2 presents two direct disposal alternatives: (A) direct disposal without a CIS facility and (B) direct disposal with a CIS facility without re-encapsulation, such as the USA model.[32-34] Both alternatives consider concrete casks with multipurpose cannister. Additionally, unlike Scenario 1, Scenario 2B assumes that the CIS facility and the DGR are located at the same emplacement.

Finally, even though it is not the strategy originally considered for Spain, Scenario 3 establishes a reprocessing strategy for Spain in which SNF is reprocessed abroad and vitrified high-level waste (HLW) is stored in a CIS facility and then transferred into a Deep Geological Repository (DGR). Uranium and plutonium are not recycled into new materials and they are considered to be kept (with a cost) in the country that reprocesses SNF.

This model, according to the material flows calculation, can be classified as a dynamic model, as it calculates the variations of the different material flows along all the stages of the back-end of the nuclear fuel cycle from the year considered as a reference (2017) and the year of the DGR closure. This calculation is based on the particularities of the scenarios considered above by means of different material flow restrictions, such as the maximum amount of waste that can be transported from one facility to another, the maximum capacity of each facility, the periods of time involved in each phase of the process, etc. Figure 2 shows the material flows for all scenarios, where Scenario 1 and 2B are represented as the same route, although the CIS facility, the type of casks and the DGR emplacement are different, as explained before, which will be considered in the costs calculation.

Finally, the model can be used for both probabilistic approaches: deterministic or stochastic. In Rodriguez-Penalonga,[27] the results were obtained as a deterministic analysis, with a subsequent sensitivity analysis. Thus, this article presents a stochastic analysis for the scenarios

TABLE 2 Spanish nuclear installations[28,30,37]

	NPP/Facility		Location	Start	End	Current status
Nuclear Power Plants	José Cabrera		Guadalajara	1968	2006	Decommissioning
	Santa María de Garoña		Burgos	1971	2012	Oncoming decommissioning
	Almaraz	Reactor 1	Cáceres	1981	2021	Under operation
		Reactor 2	Cáceres	1984	2023	Under operation
	Ascó	Reactor 1	Tarragona	1984	2023	Under operation
		Reactor 2	Tarragona	1986	2025	Under operation
	Cofrentes		Valencia	1985	2024	Under operation
	Vandellós	Reactor 1	Tarragona	1972	1989	Decommissioning
		Reactor 2	Tarragona	1988	2027	Under operation
	Trillo		Guadalajara	1988	2028	Under operation
ISFSIs	José Cabrera		Guadalajara	2006	–	Under operation
	Santa Mª de Garoña		Burgos	2018	–	Under operation
	Almaraz		Cáceres	2018	–	Under operation
	Ascó		Tarragona	2011	–	Under operation
	Cofrentes		Valencia	2021	–	Under construction
	Vandellós		Tarragona	2024	–	Future project
	Trillo		Guadalajara	2002	–	Under operation
Other	Centralised Interim Storage		Cuenca		–	Project
	Deep Geological Repository		Unknown	–	–	

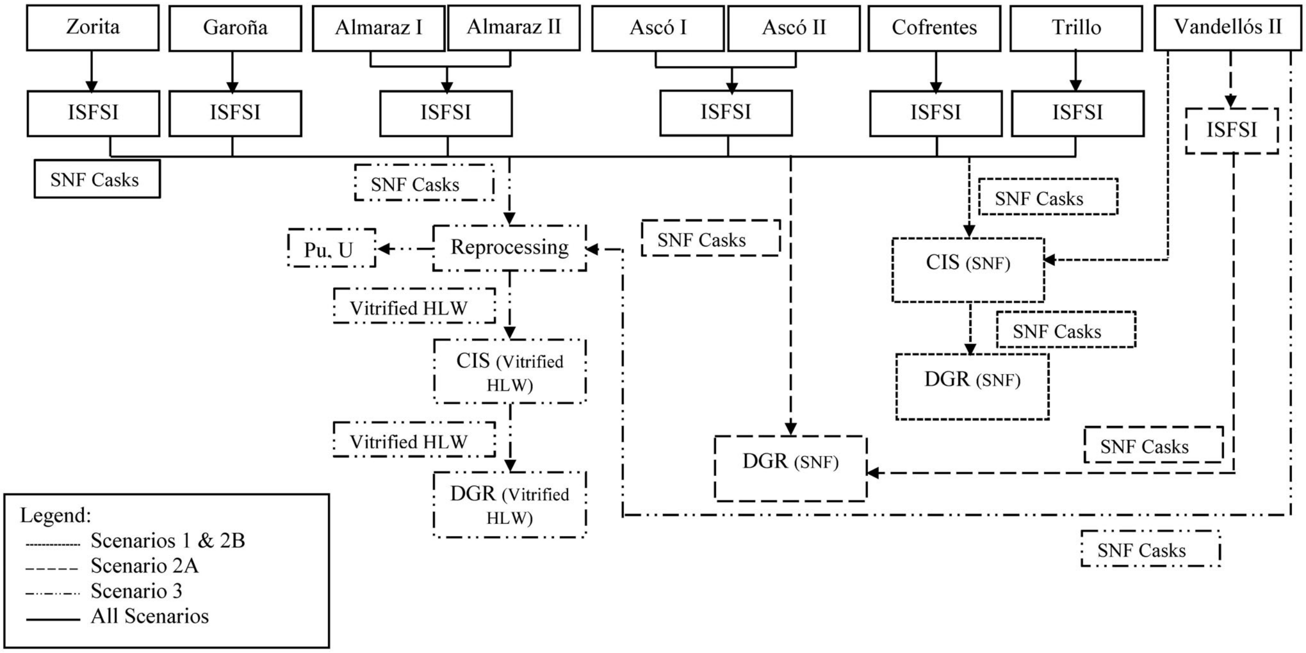

FIGURE 2 Schematic material flows for all scenarios

presented above. Additionally, a deterministic analysis will be performed to consider the effects of the variation of the NPPs operational lifetime on the total cost and on the levelized costs, as was explained before.

3 | PARAMETRIZATION

The model requires a series of parameters to obtain the results. There are two main types of parameters: restrictions for the material flows calculations and unitary costs. Amongst the first type, there can either be dates or capacities. The most important dates for the model, and the ones that the other dates are based on, are the nuclear power plants shutdown. In this article, the main assumption will be the official published dates for the NPPs shutdown, which can be seen in Table 2. However, as it is the purpose of this article, these results will be compared to other NPPs shutdown scenarios, which will be based on a progressive shutdown of the NPPs at 40, 45, 50, 55 and 60 years of operational lifetime. This progressive shutdown means that a NPP will be shut down every couple of years, in order to avoid the concentration of the decommissioning of seven reactors in 5 years. The progressive shutdown at 50 years of operational lifetime has been further analysed in Rodriguez-Penalonga.[27]

For the calculation of the costs, the year of reference is 2017. Thus, the construction and start of operation dates are the ones that were planned then. Additionally, Table 3 shows a series of restrictions used by the model

TABLE 3 Restrictions for the material flows calculations

Parameter	Value
Start of operation for the CIS facility with re-encapsulation	2025
Start of operation for the CIS facility without re-encapsulation	The year of the first NPP shutdown
Start of operation for the DGR	26 years after the last NPP shutdown
Start of reprocessing	2020
Time the vitrified HLW stays in the country that reprocesses	20
Max. No. of transports to the ISFSIs (annual)	25
Max. No. of transports to the CIS facility with re-encapsulation (annual)	40
Max. No. of transports to the CIS facility without re-encapsulation (annual)	50
Max. No. of transports to reprocessing (annual)	30
Max. No. of transports from reprocessing (annual)	12
Max. No. of transports to the DGR (annual)	50
No. of vitrified HLW capsules per tHM	1.3
No. of capsules per vitrified HLW casks	28

TABLE 4 Cost assumptions[a]

Type	ISFSI	CIS	CIS (US)	DGR[b]	Units
Investment (fixed)	15	275	90	670	M€
Investment (variable)	0.15	1.25	0.409	0.359	M€/cask
O&M (First years)	0.5	17	12	65	M€/year
O&M (Last years)	2	35	6		M€/year
Loading & transportation	0.8	0.9	0.9	0.9	M€/cask
Decommissioning	15	15	15	260	[c]
Multipurpose concrete casks canister type	1.3				M€/cask
Dual purpose metal casks	2.5				M€/cask
Reprocessing	1000				€/kgHM
Plutonium disposal	500				€/kgHM
Discount rate	1.5				%

[a]Source:[27].
[b]The DGR cost for vitrified waste is assumed to be 40% of the DGR costs for SNF.
[c]ISFSI and CIS decommissioning costs are in % of the total investment cost and DGR decommissioning cost is in M€.

TABLE 5 Unitary costs values for the density distribution

		Density function values		
Type of cost		Min.	Nominal	Max.
ISFSIs	Investment (fixed)	10	15	20
	Investment (variable)	0.1% of the fixed investment cost		
	O&M	0.4	0.5	2.5
	O&M 2	Ratio between O&M/O&M(2) maintained		
CIS	Investment (fixed)	170	275	525
	Investment (variable)	Ratio between fixed/variable maintained		
	O&M	Ratio between investment/O&M maintained		
	O&M 2	Ratio between O&M/O&M (2) maintained		
CIS (US)	Investment (fixed)	79	90	200
	Investment (variable)	Ratio between fixed/variable maintained		
	O&M	4	17	20
	O&M 2	Ratio between O&M/O&M (2) maintained		
ISFSIs and CIS decommissioning		15% of the total investment cost		
DGR	Investment (total)	700	1000	3000
	Investment (fixed)	Ratio between fixed/total maintained		
	Investment (variable)	Ratio between fixed/variable maintained		
	O&M	Ratio between investment/O&M maintained		
	Decommissioning	Ratio between investment/decommissioning maintained		
Load/transportation		0.07	0.9	1.8
Concrete casks (MPC)		0.58	1.3	1.5
Metal casks (DPC)		1.10	2.5	2.75
Reprocessing		500	1000	2100
Plutonium		−500	500	1000

in order to calculate the material flows and Table 4 shows the parametrization of the costs, which was obtained through a series of analyses of the assumptions of different international studies and reports regarding the economic analysis of the nuclear fuel cycle, such as the MIT study by de Roo and Parsons,[9,10] the OCDE,[2] the reprocessing cost in the US,[35] the study of Ko and Gao,[12] Harvard[6] and BCG,[7] amongst others, such as real data from Finland,[39] Sweden[40] and Spain[36,38,41] These analyses are further explained in Rodriguez-Penalonga.[27]

Therefore, Table 4 presents a breakdown of the different unitary costs for each facility involved in the different scenarios. Firstly, the fixed (in M€) and the variable (M€/cask) part of the investment cost are presented for each facility. Secondly, the operation and maintenance (O&M) cost is presented. The difference indicated between the first years and the last years is applied differently for each facility: (a) for the ISFSIs, the change is derived from the decommissioning of the correspondent NPP, (b) for the two CIS facilities, the first years correspond to the transportation of casks into the facility, and the "last years" start when the transportation ceases, and (c) for the DGR it does not apply.

Thirdly, the loading and transportation costs are referred as follows: the first column corresponds to the loading of SNF into the casks; the second, to cost of transportation (unitary, in M€/cask) between the ISFSIs and the current CIS facility; the third to the same transportation but to the new design for the CIS facility; and finally the fourth column corresponds to the transportation to the DGR facility.

Then, the decommissioning cost is expressed as a percentage of the total investment cost for all installations except the DGR, which is presented as a fixed value in M €. The unitary costs for the different type of casks is shown below in M€/cask: the first type (concrete) is used for Scenarios 2A and 2B, and cannot be reutilized; the second type (metal) is used for Scenarios 1 and 3 and the casks are reutilized once the CIS facility starts operating, or the reprocessing begins. Finally, the reprocessing cost, the cost of the plutonium (which is the cost of keeping the Pu in the country that reprocesses) and the discount rate, which is calculated as a real discount rate, considering the inflation, are presented.

Additionally, for the Monte Carlo analysis, the unitary costs distribution is required. For this purpose, a triangular distribution is assumed, as usually used for these types of costs.[1] For this distribution, there are three values required: the maximum, the minimum and the nominal value. For the first two, the maximum and minimum gathered from different international studies are used. For the latter, the values presented in Table 4 are assumed. Table 5 shows the parameterisation of the density distributions of each unitary cost.

4 | DISCUSSION OF THE RESULTS

As explained before, this article has two main purposes: (a) to perform a Monte Carlo analysis with the Mariño model and (b) to analyse the effect of the NPPs operational lifetime on the costs of SNF management in Spain, also with the Mariño model. In order to obtain the first results, the triangular density distributions values for each cost shown in Table 5 were used to obtain 10 000 different possible values. Then, the costs for each SNF management scenario were obtained for those 10 000 cases. Figure 3 shows the range of possible costs that each scenario can adopt as a function of the relative probability. As can be observed, Scenario 3 has a much wider range than the other scenarios and it has a greater probability of having a significantly higher cost than the direct disposal strategies. However, there is an intersection among the Scenario 3 range and the other three scenarios, which means that reprocessing could entail the same or even slightly lower costs than the direct disposal strategies, although the probability of this is really low.

Since Scenario 3 has a much wider range than the others, Figure 4 shows the results for only the direct disposal strategies (Scenarios 1, 2A and 2B) in order to better observe the results for these scenarios. As can be observed in Figure 4, Scenario 2A has the higher probability of having the lower costs, while Scenario 1 can have significantly higher costs, but with a greater variance, which means that it could also have lower cost, but with a much lower probability.

The probable ranges for all scenarios can be observed in Figures 3 and 4: (a) 3100 to 7600 M€ for Scenario 1, with atypical values up to 8300 M€, (b) 2100 to5100 M € for Scenario 2A, with atypical values up to 5400 M€, (c) 2400 to 5500 M€, with atypical values up to 6000 M€ for Scenario 2B and (d) 5000 to 22 000 M€, with atypical

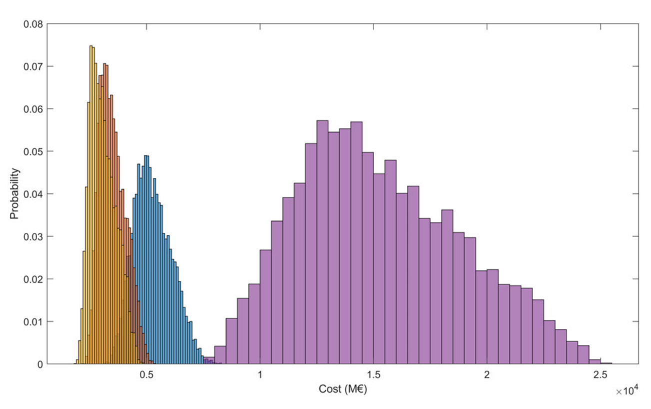

FIGURE 3 Monte Carlo simulations for all scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

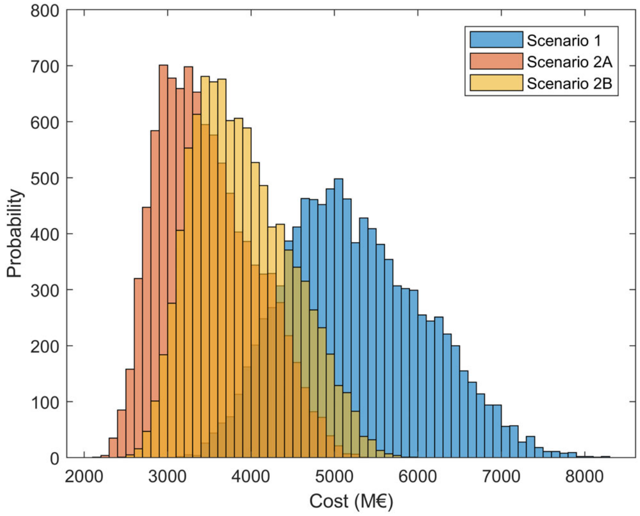

FIGURE 4 Monte Carlo simulations for direct disposal scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

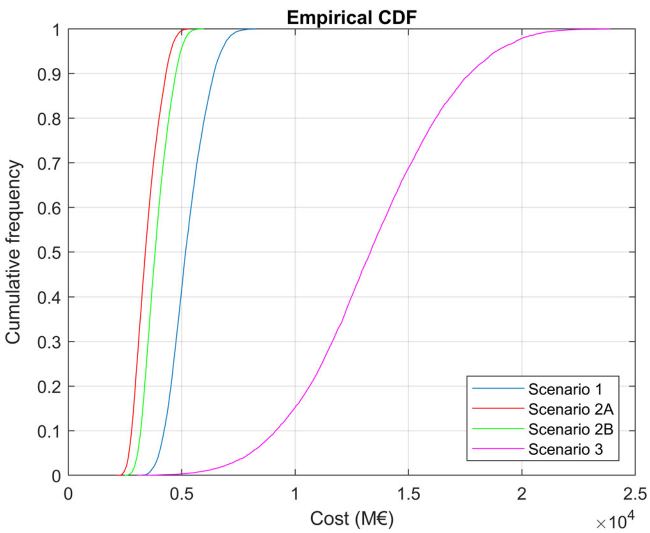

FIGURE 5 Cost versus cumulative frequency for all scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

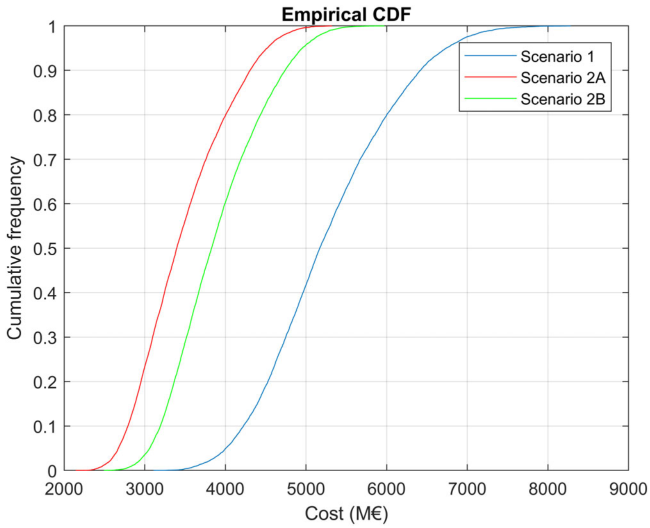

FIGURE 6 Cost versus cumulative frequency for direct disposal scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

values down to 3000 or up to 24 000 M€ for Scenario 3. Additionally, it can also be observed that Scenarios 2A and 2B have a more asymmetric distribution than scenarios 1 and 3, which are very similar to a normal distribution. Since the asymmetry has a positive skew, the mode and the median are lower than the mean, which implies that both Scenario 2A and Scenario 2B have a higher probability of having lower costs.

Finally, Figure 5 shows the cumulative probability for all scenarios and Figure 6 for the direct disposal strategies. With these Figures, the most probable cost can be calculated: (a) Scenario 1 has a 50% probability of having a cost lower than 5100 M€, (b) Scenario 2A has a 50% chance of having a lower cost than 3300 M€, (c) Scenario 2B, has the same probability of having a cost lower than 3800 M€ and (d) Scenario 3, lower than 13 300 M€. These results reinforce the Scenario 2A preference shown before and in Rodriguez-Penalonga.[16]

Finally, the intersections among different scenarios can be calculated, which translates into the probability of having the same cost. Thus, Table 6 shows the calculation of these intersections. Firstly, columns 1 and 2 show the minimum and maximum value of the intersection range, which corresponds to the maximum value of the inferior range of the intersection and to the minimum value of the superior range of the intersection, respectively. Secondly, columns 3 and 4 show the probability of having a higher cost than the minimum, and columns 5 and 6, the probability of having a lower cost than the maximum. Finally, the last column shows the probability of the intersection between both scenarios. As can be observed, Scenario 2A and 2B have a great probability of intersection, which means that they probably will have really similar costs. Additionally, it can be observed that there is a 6% intersection between Scenario 1 and Scenario 3, which is not very high, but it still could translate into Scenario 3 having a similar cost to Scenario 1, albeit with a small probability.

For the second purpose of the article, Table 7 shows the results obtained by the model using the parametrization explained in the previous section for the official NPP shutdown scenario. As can be observed, Scenario 2A presents the lowest costs, with a 39.2% decrease compared to Scenario 1. Scenario 2B also reduces the costs of Scenario 1, about a 31.2%. However, Scenario 3 has the highest

TABLE 6 Calculation of the intersections among all scenarios

Intersection	Range		Probability				
	Min.	Max.	Minimum		Maximum		Intersection (%)
Scenario 1–Scenario 2A	3.100	5.300	$P(2A \geq \min)$	69.9%	$P(1 \leq \text{máx.})$	59.4%	41.5
Scenario 1–Scenario 2B	3.100	5.900	$P(2B \geq \min)$	93.7%	$P(1 \leq \text{máx.})$	79.9%	74.9
Scenario 1–Scenario 3	3.100	23.800	$P(1 \geq \min)$	100%	$P(3 \leq \text{máx.})$	6.0%	6.0
Scenario 2A–Scenario 2B	2.400	5.300	$P(2A \geq \min)$	99.6%	$P(2B \leq \text{máx.})$	99.4%	99.0
Scenario 2A–Scenario 3	3.000	5.300	$P(2A \geq \min)$	76.7%	$P(3 \leq \text{máx.})$	0.5%	0.4
Scenario 2B–Scenario 3	3.000	5.900	$P(2B \geq \min)$	96.5%	$P(2B \leq \text{máx.})$	1.0%	0.95

TABLE 7 Costs (in M€) for the official shutdown scenario

Cost	Scenario 1	Scenario 2A	Scenario 2B	Scenario 3
Investment	1439.52	607.94	869.19	628.49
Expansion	0.00	26.36	0.00	0.00
O&M	1139.79	716.80	694.32	307.88
Casks	453.94	554.75	537.72	215.58
Loading	323.70	341.39	330.91	313.00
Transportation	837.93	250.23	402.96	579.99
Decommissioning	141.50	138.17	147.59	76.22
Reprocessing	0.00	0.00	0.00	5976.82
Pu management	0.00	0.00	0.00	2988.41
Total	4336.37	2635.63	2982.69	11 086.40

costs by far, with a 155.7% increment compared to Scenario 1, which is due to the high reprocessing costs, as they take over 80% of the total cost, and the lack of a recycling program that benefits from the use of Pu and U in MOX fuel.

These results are compared with the results of the progressive shutdown from 40 to 60 years in Table 8. It should be noted that there is a difference in the real operational lifetime of the NPPs for each time scenario, as for the official shutdown dates, five reactors shut down at 39 years of operational lifetime while for the other two it occurs at 40 years of operational lifetime. However, for the progressive shutdown scenarios, the difference on the years of operational lifetime amongst the different reactors is wider, and the year presented is just an indicative mean value.

Considering this, for Scenario 1 and Scenario 2A, besides the benefits that it would imply for the decommissioning of the NPPs, the change from the official shutdown dates to the progressive shutdown scenario at 40 years of operational lifetime would be beneficial for the back-end costs. Nonetheless, the opposite occurs for Scenarios 2B and 3. For Scenario 3, this is due to the decrease in the SNF that needs to be reprocessed. In order to examine these results more deeply, Figure 7 shows the graphical representation of the results.

As the quantity of SNF increases, it is logical to assume that the costs are going to increase, as facilities would require a greater capacity and, probably, more years of transportation and O&M. These expected results are obtained for Scenario 3, shown in Figure 7. Every increase in the NPPs operational lifetime translates into an increment of the final costs, which are due, as explained before, to the higher tHM to be reprocessed. Since the date of the start of reprocessing does not vary, there are not significant changes in the other costs.

However, this does not occur for the other scenarios. First, Scenario 1, shown in Figure 7, presents the expected trend from 45 years onwards, but before that, the increases in the operational lifetime cause the costs to decrease. This is due to the fixed operation date of the CIS facility: for a scenario with a mean NPPs operational lifetime of less than 45 years, the first reactor shutdown occurs prior to the start of operation of the CIS facility. Thus, the SNF that is stored in the pools has to be transferred into the ISFSIs facilities in order to start the decommissioning. Since in Scenario 1 the casks can be reused once the CIS facility starts operating, and in this situation the CIS facility is not yet operating, this will require more casks to be purchased compared to the situations with longer NPPs operational lifetime. Another

TABLE 8 Costs (in M€) for the different shutdown scenarios

Shutdown	Scenario 1	Scenario 2A	Scenario 2B	Scenario 3
Official	4336.37	2635.63	2982.69	11 086.40
40 progressive	4302.86	2615.81	3029.43	11 631.14
45 progressive	4228.99	2614.37	3017.62	12 169.23
50 progressive	4340.21	2653.97	3079.82	12 820.68
55 progressive	4427.36	2664.76	3109.22	13 506.28
60 progressive	4523.94	2671.09	3102.72	14 126.71

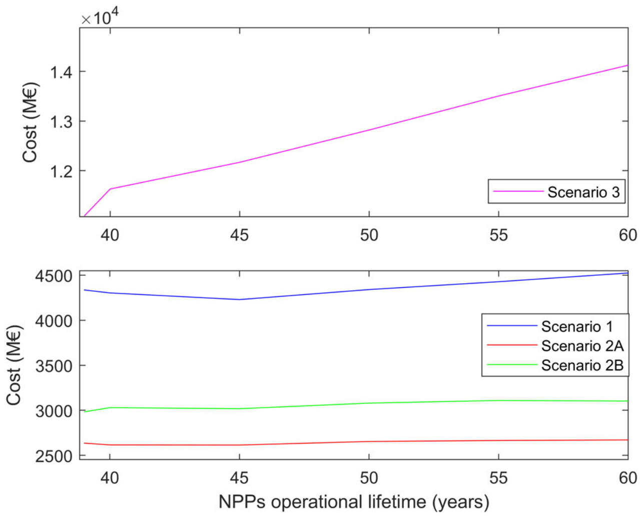

FIGURE 7 Costs variation with NPP operational lifetimes [Colour figure can be viewed at wileyonlinelibrary.com]

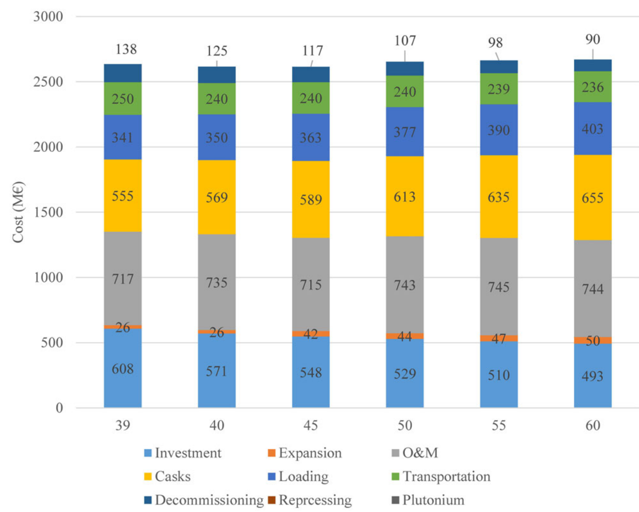

FIGURE 9 Scenario 2A costs breakdown [Colour figure can be viewed at wileyonlinelibrary.com]

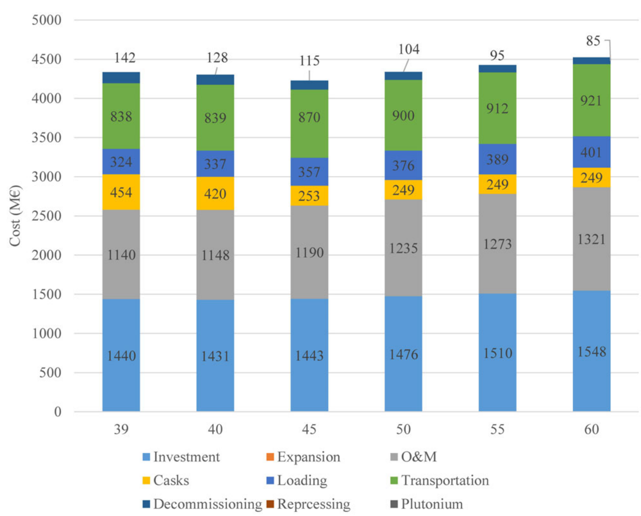

FIGURE 8 Scenario 1 costs breakdown [Colour figure can be viewed at wileyonlinelibrary.com]

cost that contributes to the decrease of the cost is the decommissioning cost, as the delay in the reactor shutdown also delays the decommissioning of other facilities.

These effects are only noticeable when the amount of casks that require purchase are significantly higher than they would have been with the CIS facility operating at the time of the first reactor shutdown, as the other cost components always increase with the quantity of SNF to be managed. Figure 8 shows the breakdown of the costs per type for Scenario 1 for the different time scenarios. As can be observed, the decommissioning cost decreases with time and the casks cost is significantly reduced from 40 to 45 years of operational lifetime. Although it still decreases from 45 to 50 years, this reduction is surpassed by the increase in all the other costs and from 50 years onwards, the casks cost is stable.

Finally, Scenarios 2A and 2B, which are shown in Figure 7, have the most unexpected results, as their costs are maintained quite stable along the different years of NPPs operational lifetime. Additionally, Scenario 2A and Scenario 2B have the opposite trend from the official shutdown scenario to the progressive shutdown at 40 years. Scenario 2A slightly decreases its costs, while Scenario 2B increases them. In order to examine these behaviours, Figures 9 and 10 show the costs breakdown for these scenarios, respectively.

For Scenario 2A, three trends can be observed for the different types of costs. First, a decreasing trend occurs

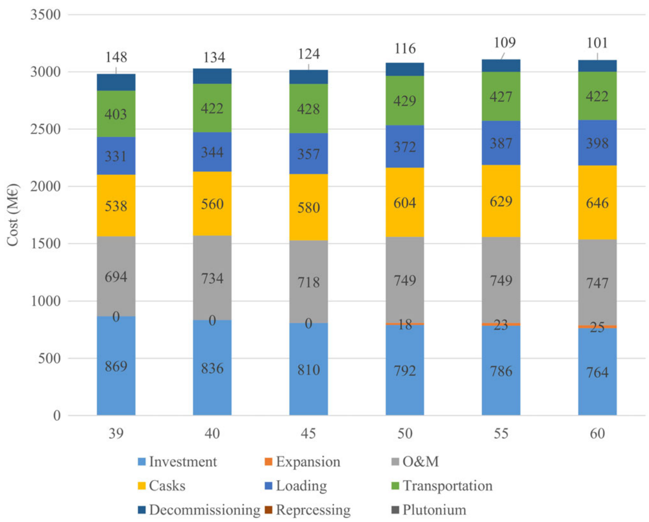

FIGURE 10 Scenario 2B costs breakdown [Colour figure can be viewed at wileyonlinelibrary.com]

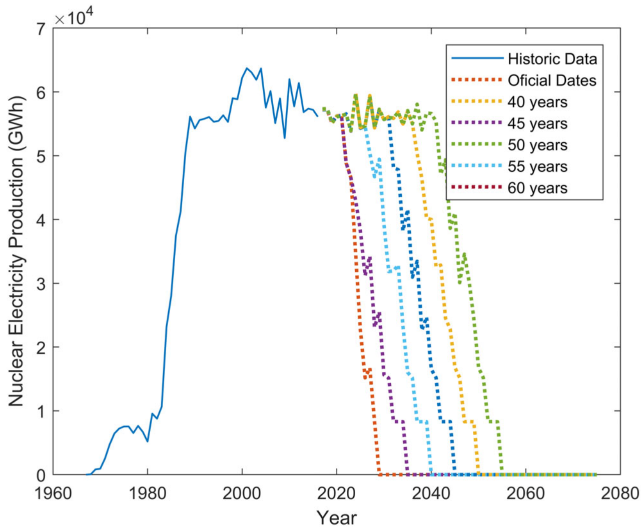

FIGURE 11 Nuclear power production estimations for the different shutdown scenarios [Colour figure can be viewed at wileyonlinelibrary.com]

for the decommissioning cost (as for Scenario 1), for the transportation cost and for the investment cost. These costs are reduced mainly to the effect of time in the discounted costs, due to the delay in the dates of these costs. Secondly, there is an increasing trend for the loading cost, the casks cost and the expansion cost. In these cases, the trend is due to the increase of SNF to be managed: more SNF requires loading into casks, more casks need to be purchased and more ISFSIs need to be enlarged. Finally, for the O&M cost, the trend is sometimes decreasing and sometimes increasing, as the effect of the delay in time can compensate the extra years of operation only in some cases.

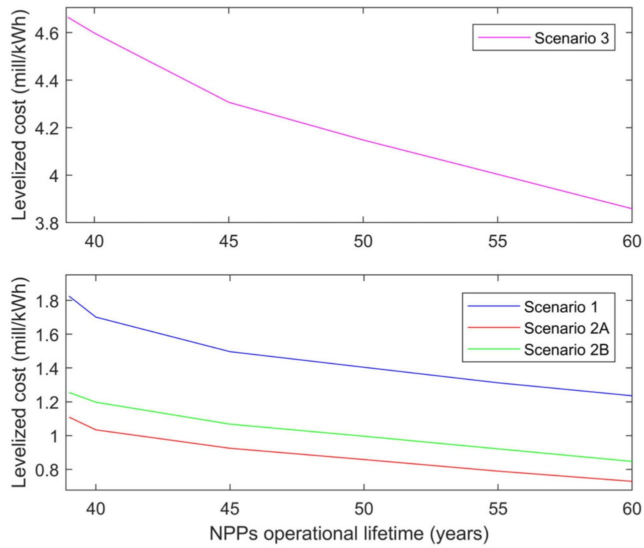

FIGURE 12 Levelized costs (mill/kWh) for different NPPs operational lifetime [Colour figure can be viewed at wileyonlinelibrary.com]

For Scenario 2B, the same trends can be observed for all costs, except for the transportation cost, that has a similar behaviour to the O&M cost, with an increasing trend until 50 years of NPPs operational lifetime and a decreasing trend from 50 years onwards. This is due to the fact that the transportation costs from the ISFSIs or pools to the CIS facility increase with the years of operation of the reactors, as the number of casks increases. However, from 50 years of mean operational lifetime onwards, the effect of the delay on the dates of transportation compensates this increase, causing the NPV to decrease.

Finally, in order to compare the levelized costs, the electricity production is estimated. For that purpose, 100 simulations are run with the model considering the probability of occurrence of the different type of outages, and the mean electricity production is calculated. Figure 11 shows the electricity production estimations for the various operational lifetime assumptions, where two main things can be observed. Firstly, that there is a significant drop in the production every time that a NPP ceases its operation, which in the official shutdown translates into a very rapid decrease in the production. Secondly, that there is a significant difference in the total electricity production between the official shutdown scenario and the progressive shutdown at 40 years of mean operational lifetime. Thirdly, that even though there are mean values, there are peaks and valleys in the estimations, which are due to the refuelling outages that occur simultaneously and are not dependant on the probability.

With these results, the levelized costs are obtained for all the scenarios, which are shown in Figure 12. It can be observed that, for all scenarios, the levelized cost has a decreasing trend, which means that the additional electricity production due to the longer NPPs operational lifetime always compensates the extra costs that this increase would entail. Furthermore, in the cases where the cost decreases due to the reasons explained before, the drop in the levelized cost is even more pronounced, as can be seen for Scenario 1, where there is a significant decrease in the cost between the official shutdown scenario and the progressive shutdown at 40 years of operational lifetime.

Additionally, it can be observed that the levelized costs decrease more rapidly for the first NPPs operational lifetime increases (up to 45 or 50 years) than for the following increments (from 55 to 60 years). This means that, when the years of operation continue to increase, the quantity of SNF and the costs associated are increasing more rapidly than the electricity production. Nonetheless, the electricity production still compensates the cost increase for all scenarios analysed.

5 | CONCLUSIONS

The Mariño model, which estimates the costs of different scenarios for SNF management in Spain by means of the material flows calculation and the net present value, has been used to perform two analyses in order to examine the different SNF management options for Spain: (a) a Monte Carlo analysis for the different scenarios, and (b) an analysis of the effects of expanding the NPPs has been performed using the Mariño model, that.

Firstly, the results of the Monte Carlo simulations show, on the one hand, that a direct disposal strategy without a centralised interim storage facility has the highest probability of having the lowest costs. However, a direct disposal strategy with a centralised interim storage facility could be an alternative, since the probability of having the same costs as the previous strategy is about 99%. On the other hand, a reprocessing strategy without Pu recycling has a high cost variance, ranging from 5000 to 22 000 M€, which could entail a much greater cost than the other strategies. Nevertheless, there is a probability of 6% of having the same costs as the current scenario, if the costs of reprocessing were reduced and/or the DGR and CIS facilities had a much higher cost.

Secondly, the results of the lifetime analysis show that for all scenarios and every increase in the NPPs operational lifetime, the electricity production compensates the extra costs that a longer-term operation of the NPPs would entail. This means that for all the strategies studied, it would always be interesting a longer NPPs operational lifetime.

Additionally, for a strategy without a centralised interim storage facility and, more interestingly, for the current strategy for Spain, a modification of the official dates for the NPPs shutdown into a progressive shutdown would entail a decrease, not only in the levelized costs, but also in the NPV. Thus, from the strategical point of view, the current NPPs shutdown scenario is far from ideal.

Finally, the model shows that a strategy without a centralised interim storage entails the lowest costs for all scenarios analysed and an increase in the NPPs operational lifetime does not result in much higher costs. On the contrary, in some cases, the costs are reduced, and the total cost is maintained in a range of 2610 to 2670 M€ throughout all NPPs operational lifetime increases. Therefore, this strategy would be the most economically favourable for Spain.

However, if a centralised interim storage option would be preferred due to logistic reasons, an alternative design without re-encapsulation would entail lower costs than the current strategy, as its cost is maintained in a range from 2980 to 3110 M€ throughout all NPPs operational lifetime increases, while, for the current strategy, this range is from 3225 to 4525 M€.

Furthermore, both direct disposal alternative strategies would have greater benefits from increasing the NPPs operational lifetime, as their costs are maintained in a slightly fluctuating but fairly constant range, while for the current direct disposal strategy, the costs start increasing more rapidly from a mean NPPs operational lifetime of 45 years.

For future research study, it would be interesting to analyse some intangible assets, such as social acceptability or environmental impact, in order to assess their importance into the decision-making process, as it will be of great importance. Additionally, the model could analyse alternative management scenarios for Spain, or be adapted to analyse the costs of different strategies for another country.

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ENDNOTE

1 Source: own elaboration from data from.[28,29]

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