How a proper spent nuclear fuel management strategy can enhance the continuity of nuclear power in the energy mix. The Mariño Model

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***Abstract*— This paper presents the Mariño Model, a model created to estimate the costs of different strategies for spent nuclear fuel management in Spain. One of the main purposes of the paper is to determine which strategy accommodates better the particularities of the Spanish context, in order to help establish a stable plan for spent nuclear management in Spain. As nuclear waste is one of the major issues towards nuclear acceptance amongst the public, if it were to be properly solved and the public is well informed and involved in the decision-making process, its acceptability could be increased. Thus, nuclear power could still have an important role in mitigating climate change.**

Keywords*— *nuclear power, spent nuclear fuel management, reprocessing, Spain

I. Introduction

Nowadays, one of the most discussed topics around the world is energy transition, whose main purpose is to mitigate climate change by means of modifying the actual model of energy generation and distribution. Renewable energies and different systems of energy storage are being the main focus of attention these days in the energy transition. However, nuclear power has proved to play a very important role in mitigating climate change for several reasons: its high productivity, its low cost per kWh produced, the security of supply, the stability that provides to the electricity grid, among others but, most importantly, the fact that it has zero direct greenhouse gas emissions and it has the lowest indirect emissions. [1] [2] [3] [4] [5]

Nonetheless, nuclear power has a lack of popularity amongst the main public, which varies from one country to another. The main reasons for this lack of popularity are the fear of an accident, the high investment costs, the long construction times and, especially amongst the public, nuclear waste [6]. This paper focuses in this last key issue: spent nuclear fuel (SNF) management. It is essential for each country that has nuclear waste to manage it safely, and for the long-lived waste (LLW) to have a stable plan and to properly involve the public in the decision-making process. [7] [8]

The public perception of nuclear power might be changed if a stable plan for its nuclear waste is established without major delays and drawbacks, which has occurred in Spain with the construction of the Centralized Interim Storage (CIS) facility that was planned to start operating in 2010 and still has not started its construction. [9] [10] Therefore, the main purpose of this paper is to present a model for SNF management in Spain that analyses the costs of different back-end scenarios in order to help determine which one accommodates better the particularities of the Spanish context..

II. Methodology

The model presented in this paper estimates the costs of different scenarios for the back-end of the nuclear fuel cycle in Spain. The costs are calculated by means of the Net Present Value (NPV) and, in order to normalize the costs in mill/kWh, then the NPV is divided by the estimated electricity production of the nuclear power plants (NPPs) along their life cycle.

A. Description of the scenarios

Currently, there are two main strategies for SNF management: direct disposal and reprocessing. In Spain, the VI General Plan for Nuclear Waste of 2006 [9] established that Spain would follow a direct disposal strategy with a Centralized Interim Storage (CIS) with re-encapsulation. Therefore, this will be Scenario 1. Additionally, Scenario 2 considers two direct disposal alternatives: A) direct disposal without CIS and B) direct disposal with CIS without re-encapsulation, such as the USA model.

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 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.

B. Description of the model

The particularities of these scenarios are considered in the model 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. These restrictions lead to a different number of SNF casks or HLW capsules that are transported each year between facilities, which are calculated by the model.

There are different types of costs that are estimated for each facility: the investment cost, the operation and maintenance (O&M) cost and the decommissioning cost. Also, there are other costs that have to be considered: the transportation cost between facilities, the cost of the casks, the cost of loading the SNF into casks from the reactor pool and, only for Scenario 3, the cost of reprocessing and the cost of managing the plutonium (Pu). As it was explained above, these costs are calculated by means of the NPV.

Finally, the future electricity production is estimated by calculating the load factor each year. This load factor is estimated using its correlation to the different types of outages. The historic electricity production from nuclear is then added to obtain the total electricity production, which is used to levelize the costs into mill/kWh.

III. Results

The parametrization of the costs was based on data gathered and assumptions that were made in different reports, studies and papers, such as [11] [12] [13] [14] [15] [16] [17] [18] [19] [20]. The time frame reference was supposed for a progressive shutdown of the NPP for a half lifetime of around 50 years, starting the first shutdown in 2031 and the last one in 2044.

Table I shows the results of the NPV for each scenario per type of cost. Scenario 2A is clearly the most economically favourable one, followed by Scenario 2B, while Scenario 3 is by far the one with the highest costs (146.5% higher than Scenario 1), which is due to the high cost of reprocessing and the lack of a recycling program which can take economical advantage from the uranium and plutonium extracted from SNF.

As can be observed, for Scenarios 1, 2A and 2B, the distribution of the costs per type of cost is fairly balanced, where the investment cost, the O&M cost and, especially for Scenario 2A, the casks cost, have a higher weight in the final cost (about 20% each). However, for Scenario 3, the distribution is less balanced, as more than a 75% of the cost comes from reprocessing and managing the Pu.

TABLE I. Total costs (M€) per type of cost

Type of cost		Scenario 1	Scenario 2A	Scenario 2B	Scenario 3
Inves-tment	Initial	1499.29	490.68	791.31	643.06
	Expan	0.00	102.46	32.97	0.00
O&M		1145.52	761.17	762.84	298.65
Casks		248.62	613.15	604.50	161.69
Cask loading		376.30	377.32	372.00	388.11
Transport		826.26	240.47	435.67	697.79
Decommission		113.23	110.84	119.59	64.18
Reprocessing		0.00	0.00	0.00	5415.83
Plutonium		0.00	0.00	0.00	2707.91
TOTAL		4209.21	2696.09	3118.89	10377.22

These costs are shown per type of facility in Fig. I. The CIS facility cost is clearly the most important one for Scenario 1, while for Scenario 2A and 2B the costs are more fairly distributed. For Scenario 3, the costs of reprocessing and managing the Pu are allocated to the independent spent fuel storage installations (ISFIs), which causes the vast difference in the distribution of the costs with the other facilities. The cost of the CIS and, especially, the DGR for this Scenario are considerably lower than the cost of these facilities for the other scenarios, because the storage of vitrified HLW is fairly lower than SNF. [19] [20]

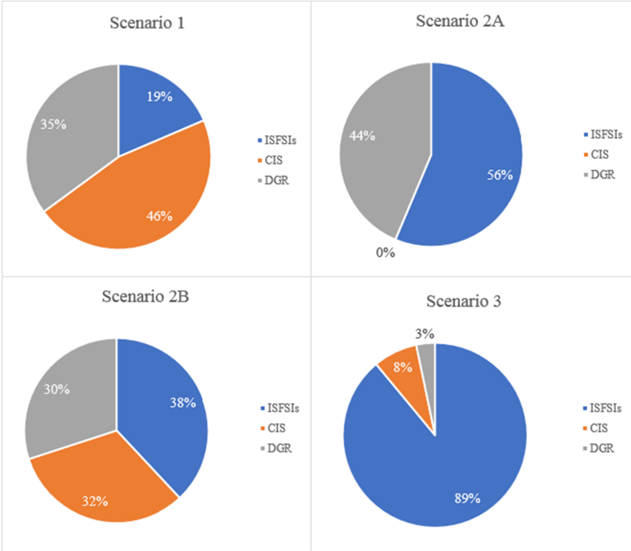

Fig. 1. Cost distribution per facility type

TABLE II. Back-end cost component of the levelized cost for different strategies in other studies (mill/kWh)

Strategy	Study: *De Roo 2009 [3]*	*De Roo 2011 [1]*	*OECD 2013 [2]*	*Mariño Model*
Direct disposal	1.3	1.31	~1 - ~2.5	0.87 - 1.01 - 1.36
Reprocessing	2.98-6.97	2.87-6.96	~2.1 - ~4	3.36

The total electricity production of the NPPs along their lifetime is considered in order to obtain the levelized cost per kWh. Table II shows the comparison among the levelized costs obtained with the Mariño Model and other international studies. As can be observed, the results of the model are consistent with the results of the different studies, which reinforces and proves the strength of the model.

IV. Conclusions

The model has proved to obtain consistent results compared to other international studies. Therefore, the model can be used to properly estimate the costs of different strategies for SNF management in Spain and to compare these results in order to establish the most favourable scenario in this particular context.

The results of the model show that, while no recycling program is established in Spain, a direct disposal strategy will always have significantly lower costs than a reprocessing strategy that only takes advantage of the easiest management of vitrified HLW and its lower volumes. Also, within the direct disposal strategies, a scenario without a CIS facility, only storing SNF in ISFIS, would suppose a decrease in the costs that would range between 16 and 68%. However, if a strategy with a CIS facility was preferred in order to store all SNF in the same location, a CIS without re-encapsulation would have the lowest costs.

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