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Research Article

Economic Analysis of the Management of the Nuclear Spent Fuel in Spain

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This study aims to analyze the economic and technical viability for either nuclear fuel reprocessing or permanent storage in Spain. Utilizing various international studies regarding nuclear fuel reprocessing, this study reaches an objective conclusion while taking into consideration the various variable and stable costs for the open and closed cycles. A sensitivity analysis was then introduced which identifies the most influential parameters in the final price. This analysis is essential in understanding the results obtained and emphasizes the need to specify a range of costs for both cycles and to see what factors affect these results. The sensitivity analysis describes the factors that play a large role in determining costs and will display the range of values that arise from the variability of costs for those factors. The uncertainty analysis compares the nominal values used in this study and describes how these values are likely to change with time resulting in a range of values for both cycles.

1. Introduction

Nowadays the cost of electricity from nuclear energy is highly competitive compared to other sources of energy. But we have to take into account that depending on the type of fuel cycle considered the final cost will vary. Because of this, determining the costs associated with each cycle option is essential in order to make the final decision of what to do with the irradiated fuel.

In Europe there are two countries, Sweden and Finland, that have chosen to use an open cycle and they have developed programs to build deep geological repositories (DGR) for the used fuel elements. On the other hand, there are two countries in Europe, France and the United Kingdom, with facilities that reprocess the nuclear fuel. However, those two countries are not the only ones that reprocess the used nuclear fuel in Europe. There are other countries, such as the Netherlands, that have made the decision of a closed nuclear fuel cycle.

Spain is among those countries that have not yet come to a final decision related to the management of the used fuel. Those countries that delayed the decision on the final destination of the used fuel are currently storing it in temporary facilities, waiting for a final decision.

In Spain, the absence of a final decision has created the need for temporary solutions. The key in the Spanish used fuel management strategy is the centralized temporary storage facility (Almacén Temporal Centralizado, ATC). Meant to receive the used fuel and high level waste from the Spanish nuclear power plants, its location was approved on December 30, 2011, by the Spanish Council of Ministers: the municipality chosen for its construction is Villar de Cañas. In that facility the used fuel generated in Spain for 40 years, around 6700 THM, will be stored for a period of 60 years.

This paper assesses the economics of the open and closed cycle in Spain. It covers the total cost of management of the used fuel in Spain for the option of direct disposal and the option of reprocessing the fuel.

2. Scenarios Considered

2.1. Open Cycle. The first scenario proposed consists of an open cycle. In this scenario it is considered that the fuel, after

Table 1: Unitary costs.

	Units	Lower bound	Nominal	Upper bound
Uranium	$/KgU_3O_8$	50	125	175
Conversion	$/KgU	13	15	17
Enrichment	$/SWU	146	162	179
Fuel fabrication				
UO_2 fuel	$/KgHM	225	250	275
MOX fuel	$/KgHM	1.368	1.520	1.672
Reprocessing	$/KgHM	700	846	1000
Transport				
Spent fuel	$/KgHM	40	50	60
HLW	$/KgHM	10	20	25
ATC facility				
Construction	M$	950	1.000	1.200
Operation	M$/year	4	5	10
Repository				
Spent fuel	$/KgHM	815	996	1.196
HLW	$/KgHM	395	680	748
Credits				
Uranium	$/KgU	129	143	157
Plutonium	$/grPu	16	18	20

being irradiated in the nuclear reactors, is stored in the spent fuel pool of the same nuclear facility. After a cooling period in this pool, the fuel will be transported to the temporary centralized storage facility, ATC, which is currently under construction. In this paper, the year 2020 has been considered the start of operation for this facility—according to a realistic schedule.

A 10-year period it has been considered to transport all the nuclear fuel from the spent fuel pools of the nuclear power plants to the temporary centralized storage facility. The ATC facility is being built to have an operational life of 60 years. After that period, the spent fuel will be transported to its final destination, the DGR. In this paper we assume that the construction of the repository will start 15 years before the end of the scheduled operation period of the ATC temporary centralized storage facility. Finally a 5-year period is considered for the transportation of the used nuclear fuel from one facility to the other.

2.2. Closed Cycle. The second scenario is the closed cycle in which the fuel is reprocessed. In this scenario, the used fuel is sent to the reprocessing plant. It is considered a European reprocessing plant in order to estimate the transport cost. The fuel will be reprocessed for 50 years, starting in 2018. After this 5-year-long reprocessing, two groups of products are obtained: on the one hand, the vitrified and compacted high level wastes (HLW), and on the other hand, both the plutonium and uranium that were present in the used fuel.

The plutonium and uranium are valuable materials that can enter in the fabrication of fresh recycled fuel, such as MOX and Enriched Recycled Uranium, currently used in different countries in the world. Therefore, in this study both materials are considered to be sold and therefore some credits are obtained. At the same time, the HLW would be progressively sent to the ATC, five years after the start of the reprocess. That high level waste only represents around 20% of the volume of the original used fuel; that is why, when it comes to storage costs at the ATC, this paper only takes into account the proportional occupied part.

After 60 years of storage period in the ATC, it would be transported to the repository. Considering that the transport of the HLW is done in 5 years and a 10-year period for the construction of the repository, the starting date of the construction of the repository should be 15 years prior the closure of the temporary facility.

3. Unit Costs

The unit costs presented in this paper are referred to using the dollar amount in 2010. Those values reported at different times were converted into the value of 2010 with an escalation rate of 5%. The values used in this paper are shown in Table 1. Due to the difficulty in estimating the absolute value for each cost because of many uncertainties, it is suggested that a nominal value as the best estimate and then a lower and an upper limit be set.

Uranium Price. It is a challenge to determine the uranium cost due to the complexity of the price determinants. Figure 1 displays the evolution of the uranium price and overlapping this data are the values chosen in different studies at the year used as reference in order to establish the cost (which may be different from the publishing year which is shown in the caption). Notice that the studies use the nominal value of the uranium at the moment in which each of the studies has been carried out. This shows the difficulty of determining

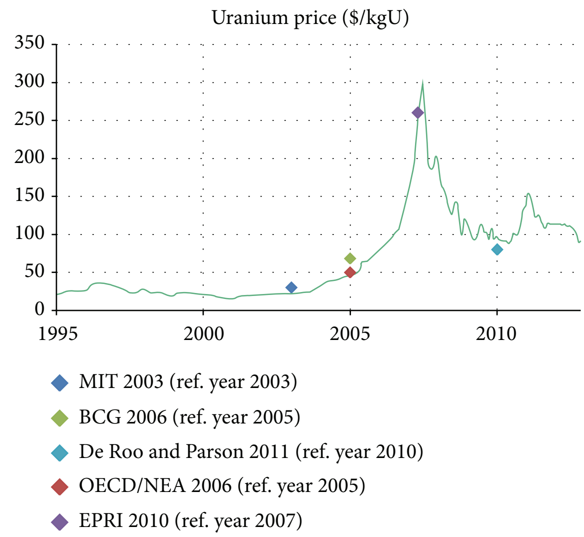


Figure 1: Uranium price.

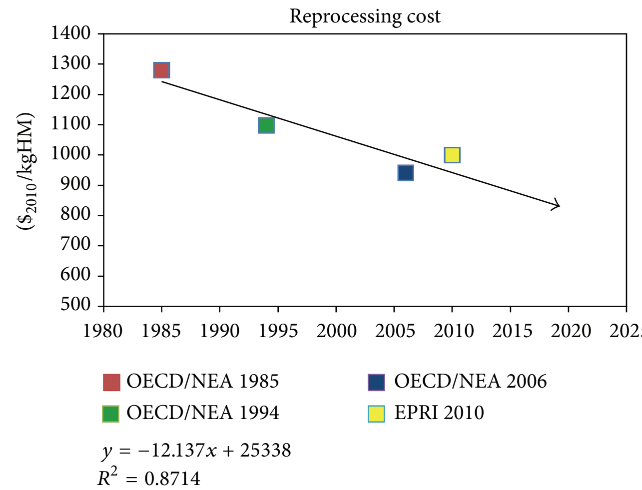


Figure 2: Reprocessing cost.

the future uranium cost. In this paper we used 125$/Kg$U_3O_8$ which seems a reasonable value for a long-term prediction.

Conversion. In this paper the value for conversion has been obtained from the OECD/NEA 2006 [1] and the EPRI 2010 [2] reports. Both studies use the same value, 15$/KgU. This is the same as the one used in this study because there are no significant changes expected and the historical analysis shows that the price of conversion is a process with a very stable cost.

Enrichment. The value of enrichment has been set at the market value for the year 2007 and has been actualized. There are a number of well-established enrichment technologies such as gas diffusion and centrifuge processes. Although the introduction of new technologies is expected to provide a better ability to enrich uranium at lower prices due to lower energy consumption, we have assumed a constant enrichment price of 162$/SWU.

Fabrication. The cost of fabrication of UO_2 fuel has decreased compared with the OCDE/NEA studies of 1994 [3] and 2006 [1]. Therefore, it is not expected that the cost will increase in the near future. Because of this the value used in this paper is the same value as in the OECD/NEA 2006 report, which is 250$/KgHM. In the case of fabrication of MOX fuel, the data has been obtained from the OECD/NEA 2006 report and actualized. The value obtained is 1520$/KgHM.

Reprocessing. The value used in this paper for the cost of reprocessing the nuclear fuel has been obtained from the tendency of four articles as shown in Figure 2. A cost of 845,5$/KgHM has been assumed for the year 2018 which is considered the year of starting the reprocess as mentioned in the second scenario. Apparently, there is a decreasing tendency that is explained by different factors. One of them is the improvement in the purity of the uranium and plutonium recovered in the process, which has an important impact over the total cost. Another area where improvement is possible and will result in a lower final cost is in the field of waste management, by reducing the amount of waste generated in this type of facility.

Transport. The transport of used fuel in the first scenario will be done between the nuclear power plants and the ATC and later from the ATC to the repository. In the second scenario the used fuel will be transported from the nuclear power plants to the reprocessing plant. It has been assumed the same cost of 50$/KgHM [1] for any of those transports of the used fuel. In the second scenario it is also necessary to transport the HLW from the reprocessing plant to the ATC and later from the ATC to the DGR. For this transport, the cost assumed is 20$/KgHM as in the BCG study of 2006 [4]; Nevertheless, the aforementioned value is for the US and in the case of Spain it could be slightly lower.

ATC Facility. The construction cost of the ATC is estimated to be 1.000$ M with an operational cost of 5$ M per year. One assumption in this paper for both scenarios is that the ATC will be operative since 2020 with a 60-year lifetime. In the first scenario, the ATC will store all the used fuel, while in the second scenario it will only store the HLW resulting from the reprocessing.

Repository. The size of the repository depends on the scenario. The first scenario requires a larger repository while the second scenario could use one which is smaller in size. This is because the HLW represent 20% of the volume of the initial spent fuel. Therefore, the cost of the repository will vary. For the first scenario we used the same source as in the 1994 OCDE/NEA study which is another study from the OCDE/NEA related to the cost of waste disposal in geological repositories. This study assumes 2 possibilities for Spain, so for this paper we took the average of the 2 and actualized it, obtaining the value of 996$/KgHM. For the second scenario the 1994 study OCDE/NEA shows the case of different countries and in the Spanish case it has been assumed in this paper the average cost of those countries with similar nuclear fuel consumption

Table 2: Parameters of the nuclear reactors.

	Cofrentes	Trillo	Almaraz-1	Almaraz-2	Asco-1	Asco-2	Vandellós-2	Garoña
P	1.092,02	1.066	1.035,27	1.044,45	1.032,5	1.027,21	1.087,14	466
ε	33,7	35,4	35,1	35,4	34,9	34,7	36,9	33,7
C^1	87,89	87,14	86,83	88,79	79,81	85,27	75,59	92,93
BU^2	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000
$\text{Annual}_{\text{req}}$	**20,79**	**19,16**	**18,7**	**19,12**	**17,24**	**18,43**	**16,26**	**9,38**

[1] Average of the years 2008, 2009, 2010, and 2011.
[2] Approximation for all the reactors.

obtaining an actualized value of 680\$/KgHM, Kg of HM extracted from the reactor.

Credits. The credits obtained from the reprocessing come from the value of the uranium and plutonium recovered from the reprocessing [5]. For the uranium the methodology used is to match the price of enriched fuel from natural uranium and the price of fuel from reprocessed uranium. The credits from the plutonium are obtained when the economic balance point between MOX fuel and fuel from natural uranium is established. The obtained values are shown in Table 1.

4. Cost Calculation

In order to determine the total amount of used fuel that will be produced in the Spanish reactors throughout their lives, the known data of used nuclear fuel produced up to 2011 which is 4227 THM [6] is used. From that date to the closure of the nuclear reactors, it is necessary to determine the amount of used fuel that will be produced. In order to do so, we used the estimation of the amount of fuel required (MTHM) by one reactor based on the reactor parameters [7] as shown in Equation (1), where P is the electric power (MWe), C is the capacity factor (%), ε is the efficiency (%), and BU the burnup (MWD/THM) and those values for each reactor are shown in Table 2:

$$\text{Annual}_{\text{req}} = \frac{P \times 365 \times C}{\varepsilon \times \text{BU}}. \quad (1)$$

With (1) it is possible to estimate the nuclear fuel required for the eight reactors that are actually in operation in Spain. The annual production of used fuel can be observed for each reactor in the last row of Table 2. For this analysis it is considered a 5-year extension from the established 40-year lifetime of the nuclear power plants. With this assumption we obtain the final value of 6676 THM.

The methodology used is the standard discounted cash flow approach to arrive at the total cost for each of the options. This methodology uses the concept of time-value of money and therefore all future cash flows for each of the two options are estimated and discounted to give their present value. The final total cost could be summarized as follows:

$$\text{Total Cost}_{\text{Discounted}} = \sum_{i=1} \sum_{t=T_0}^{t=T_1} \frac{F_i(t)}{(1+r)^{t-t_r}}, \quad (2)$$

where "i" indicates each of the cycle components for each of the scenarios and T_0/T_1 indicate the beginning and end of the period in which the cost of each component is incurred in regard to time. Therefore, $F_i(t)$ represents the total cost associated with a component of the cycle in the year "t." The other two parameters "r" and "t_r" represent the discount rate and the time reference at which all the costs are actualized, respectively.

For both scenarios the time period analyzed goes from 2013 to 2080. That is because the objective of this analysis is to give an estimate of the total cost of the management of the nuclear fuel in Spian and the beginning is considered to be the construction of the ATC which is the year 2013 and assumes that the ATC will start to operate in the year 2020. After the 60 years of lifetime the ATC has to be ready for the closure and therefore by that date a deep geological repository has to be ready.

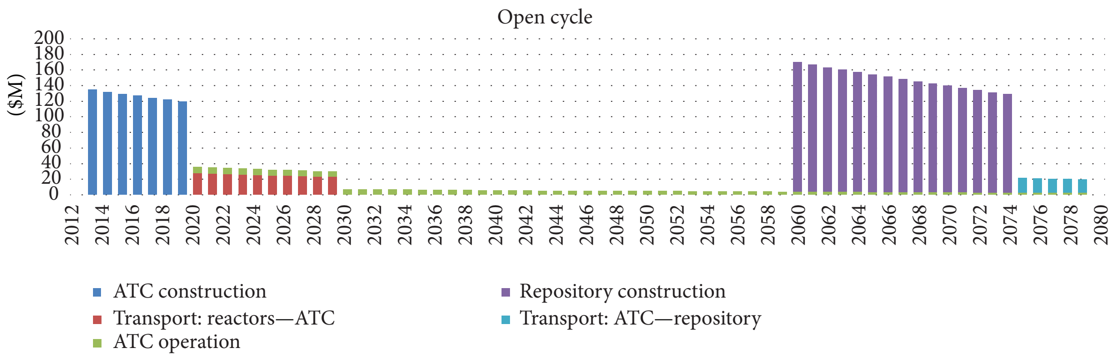
5. Results and Discussions

The results obtained in this study have shown a closed cycle option cost of 582\$ per Kg of irradiated fuel extracted from the reactor. In the scenario of an open cycle option the cost is slightly lower, 533\$. This means that the closed cycle has 9.2% higher cost than the open cycle. Figure 3 shows the yearly cost distribution for both alternatives.

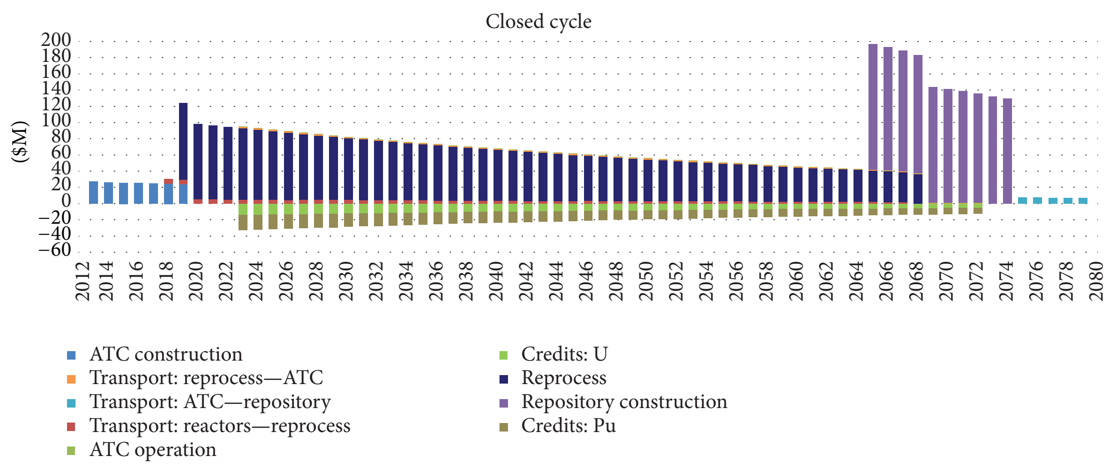
Due to the uncertainties and difficulties in the estimation of some of the parameters it is considered that the nominal value is a good reference for the magnitude of the cost but it is not enough; therefore, a range of values with a certain confidence level should be provided. In order to do so an uncertainty analysis is required. A sensitivity analysis is also shown in this paper to reveal which are the most determinant parameters when determining the final cost of the management of the used nuclear fuel.

5.1. Uncertainty Analysis. This analysis is done using the Monte Carlo method; this method generates random samples from a known distribution. Therefore, the first step is to assign a certain distribution to the different unit costs. For this paper, triangular distributions have been used for the costs. The triangular distribution is characterized by being a continuous function having a lower limit, a mode, and an upper limit. For each cost the mode will be the nominal value and the lower and upper limit will be lower and upper bound shown in Table 1. The results with a total of 100.000 extractions performed are shown in Figure 4 and Table 3.

Considering a confidence level of 95% after a fit with normal distributions we obtain the intervals shown in Figures 5



(a)



(b)

Figure 3: Open and closed cycles cost distribution.

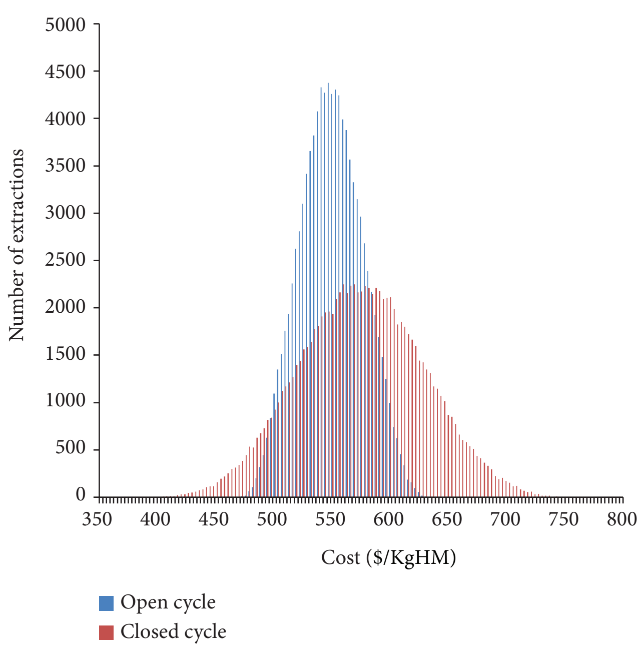


Figure 4: Comparison of the two alternatives for 100.000 extractions.

Table 3: Parameters of the Monte Carlo simulation.

	Open cycle	Closed cycle
Maximum	634,53	771,44
Minimum	468,14	372,77
Average	547,97	573,04
Standard deviation	27,3	54,35

and 6. It is noticeable that the interval is considerably large in the closed cycle which goes from 467$ to 680$ than in the open cycle from 494$ to 601$ per kilogram of heavy metal extracted from the reactor.

The standard deviation is smaller in the open cycle, 27$/KgHM, than in the closed cycle, 54$/KgHM. This means that the open cycle cost is less likely to incur possible changes of the unitary costs of the different parameters. This is reasonable because as it is shown later in the sensitivity analysis, the variations of the reprocessing cost may have a big impact over the nominal scenario, similar to uranium price or repository cost but with the difference that reprocessing only affects the closed cycle cost while the other two affect the cost of both alternatives.

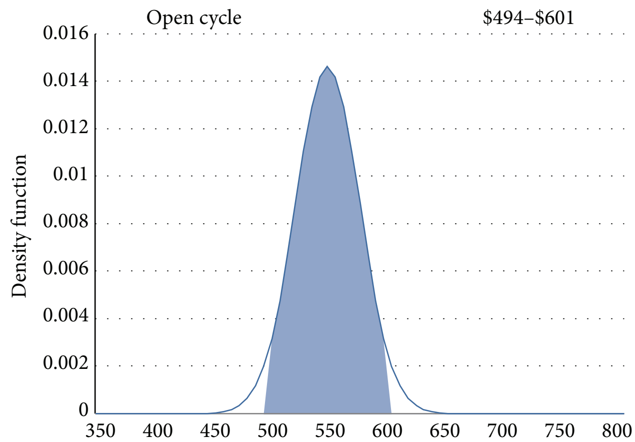


Figure 5: Range for open cycle.

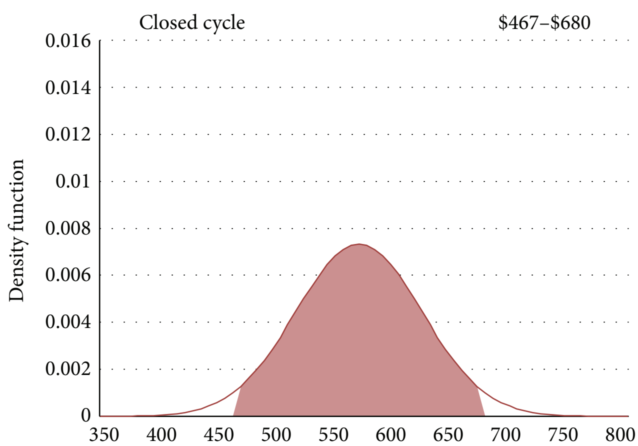


Figure 6: Range for closed cycle.

5.2. Sensitivity Analysis. The purpose of this analysis is to show, given the variation of the different unit costs, which of the parameters are those that most affect the possible variation of the final result. The ranges of variation of the different costs are shown in Table 1. Figure 7 shows the results of the sensitivity analysis.

The results shown in Figure 7 correspond to the impact that the variations on the unitary costs have over the nominal case. For example, if the long-term uranium price stays at 50\$/KgU_3O_8, the lower bound, instead of the nominal value, 125\$/KgU_3O_8, that will benefit the open cycle option in approximately 100\$/KgHM compared to the nominal scenario. This means that the open cycle becomes 149\$/KgHM more economical than the closed cycle. On the other hand, if the long-term uranium price stays at the upper bound value, 175\$/KgU_3O_8, that benefits the closed cycle option in around 68\$/KgHM compared to the nominal case. This means that if this was the case the closed cycle becomes a better option from an economic point of view. And the difference between the closed cycle and the open cycle will become 19\$/KgHM in favor of the closed cycle.

This shows that with either variation, one scenario can be more cost effective than the other. If there was a variation bigger than 49\$/KgHM, that is the difference in the nominal case, in favor of the closed cycle that would mean that the closed cycle becomes the more economical option. On the other hand, any variation in favor of the open cycle will make a bigger gap between the costs of both scenarios and the open cycle will be an even better option from an economic point of view.

There are three factors that are the most determinant ones and thus they have a bigger impact over the final cost. These are the uranium costs, reprocessing cost, and repository. These results are similar to those obtained by other studies. For example, the study from the BCG 2006 [4] considers that the uranium and the repository are the two key factors when determining the total cost. That study even shows how these two costs have an increasing tendency which in a long period of time will favor the closed cycle.

The study from the OCDE/NEA 1994 [3] considers the uranium as the most important factor due to the difficulty to estimate its cost in the long term. But in this study it is also mentioned that the reprocessing cost is a key factor that can significantly reduce the closed cycle cost making it more competitive from an economic point of view.

6. Conclusions

The results obtained in this paper show that the cost of management of the nuclear fuel through the closed cycle in the nominal case is 9.2% greater than in the case of an open cycle. This difference is not enough to justify taking one option and forgetting the other. Consequently there are other parameters different from the economic ones that should be taken into account when discussing the two options.

It is also necessary to take a look at the tendency of those three factors that were established as the most determinant in predicting future changes in the total cost of each of the alternatives. The cost of reprocessing the nuclear fuel as it is shown in Figure 2 has a decreasing tendency which is in favor of the closed cycle, as presented in the previous works [8, 9], while cost estimates for the construction of a repository are increasing. The clearest case occurs in the United States with the Yucca Mountain project where the costs have increased each time they have been reviewed, due to factors such as strong and more expensive security measures and more requirements in the design. This tendency is also in favor of the closed cycle. The last of the three parameters established as the most crucial of all is the uranium cost. Although the future price of uranium is hard to predict, the most likely scenario shows an increase that would benefit the closed cycle alternative.

The analysis of uncertainty shown in this paper gives a more realistic point of view of the total cost for each of the two scenarios proposed. The results show a range of values with a 95% confidence level between 494\$ and 601\$ per Kg of HM in the open cycle scenario and a range between 467\$ and 680\$ for the closed cycle scenario.

For all of these, it is concluded that an open cycle option is slightly more economical in the short term in Spain.

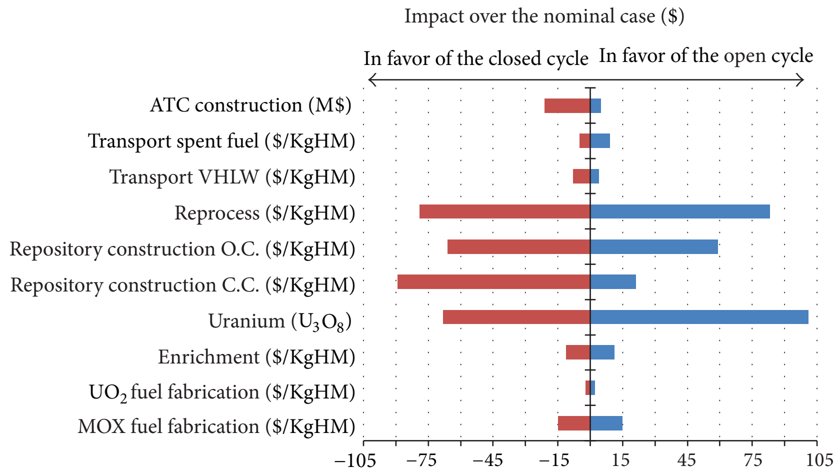


FIGURE 7: Sensitivity analysis.

Nevertheless, this will change in the long term, making the closed cycle competitive or even cheaper than the open cycle. Also it is necessary to keep in mind that ENRESA, the state owned company in charge of the nuclear waste and the used fuel management in Spain, currently works with an open cycle model. Changing to a closed cycle model will imply new developments in legislation in order to regulate the nuclear reprocessing activities; also, it would be necessary to find buyers for the useful products of this reprocess, in order to obtain the credits considered in this paper.

However, despite those considerations, the reprocessing option has a number of benefits that have to be taken into account when facing the decision related to the management of the used fuel. Among others, it is important to consider that the amount of final waste would significantly decrease, being approximately one-fifth of the volume of the equivalent used fuel in the open cycle option. This option also reduces the consumption of natural uranium, which means some benefits for the environment due to the reduction of the necessary mines to satisfy the needs of fresh fuel in the nuclear power plants. It also makes the nuclear energy more sustainable because the row materials will be available for a longer period of time. And last but not least, this option may be more supported by public opinion because smaller amount of waste will have to be stored for a shorter period of time when comparing to an open cycle option.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] OECD/NEA, *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, OECD, Paris, France, 2006.

[2] EPRI, "An economic analysis of select fuel cycles using the steady-state analysis model for advanced fuel cycles schemes (SMAFS)," Tech. Rep. no. 1015387, Palo Alto, Calif, USA, 2007.

[3] OECD/NEA, *The Economics of the Nuclear Fuel Cycle*, OECD, Paris, France, 1994.

[4] BCG, "Economic assessment of used nuclear fuel management in the United States," 2006.

[5] OECD/NEA, *Plutonium Fuel: An Assessment*, OECD, Paris, France, 1989.

[6] "Seminario Permanente de Tecnologías Energéticas: Ciclo Combustible Nuclear," Gestión del Combustible Nuclear, UNESA, Lorenzo Francia, 2012.

[7] W. Ko and F. Gao, "Economic analysis of different nuclear fuel cycle options," *Science and Technology of Nuclear Installations*, vol. 2012, Article ID 293467, 10 pages, 2012.

[8] B. Y. Moratilla, M. Uris, M. Estadieu, A. Villar, and D. Echevarria, "Recycling versus long term storage of nuclear fuel: economic factors," *Science and Technology of Nuclear Installations*, vol. 2013, Article ID 417048, 7 pages, 2013.

[9] B. Y. Moratilla and A. Villar, "Influence of the new Spanish legislation concerning the management of nuclear waste," *Science and Technology of Nuclear Installations*, vol. 2013, Article ID 316414, 7 pages, 2013.