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AN ANALYSIS OF THE PROPERTIES OF LEVELIZED COST ANALYSIS OF STORAGE OR RECYCLING OF SPENT NUCLEAR FUEL

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ABSTRACT

The demand for reduction of carbon dioxide emissions in the processes of electricity generation, plus the demand for firm energy matrices, make the nuclear matrix a central component to occupy the energy mix during the next hundred years. Increasing the share of nuclear power in electricity production in a multiple developing countries will lead to increased spent fuel production. Thus, the managing radioactive waste amining to decide about storing or recycling it is a central issue to be addressed by environmental management and nuclear energy communities. In this manuscript we present our studies aiming to understand the levelized analysis of cost of electricity generation comparing storage or recycling of the spent fuel.

1. INTRODUCTION

The increasing demand for electricity by developing countries and the need for decarbonizing the global energetic mix will demand an increasing on the use of nuclear power. Hence, the amount of used nuclear fuel will be increased and that will lead society towards the search of a solution for nuclear fuel management by either storaging or recycling. This subject is important to be approached since it has environmental, social and economical implications. Naturally, there will be concerns about the destination to be given to the spent fuel as nuclear energy generation increases. In a scenary where pacific usage is ensured, as widely discussed by International Atomic Energy Agency of UN (IAEA-UN, 2008), a central discussion is on the choice between recycling or storaging the irradiated fuel.

The search for a solution for the spent nuclear fuel is likely to demand efforts from multiple nations to develop technically and economically viable approaches for this issue (IAEA-UN, 2008) (EASAC, 2014). The multilateral efforts are expected to reduce concerns with proliferation caused by spent fuel management. Another important goal is to maximize the benefits obtained from use of natural resources and to reduce the volume of radioactive materials to be shielded and safely displaced. The reduction of the volume of spent nuclear fuel and their half life may be achieved by transmutation of the actinides composing them by means of economically viable advanced techniques (Soria et al., 2013) (OECD, 1994).

Two options for managing spent fuel have recently been highlighted: deposition in long-term geological repositories (open fuel cycle) and reprocessing (closed fuel cycle). The choice of one of the two alternatives depends on their economical viability (Soria et al., 2013) (Idaho National Lab, 2010) (Harvard University, 2003). One element of that comparison is the establishment of a cut-off criteria to determine the threshold at which urainium reprocessing becomes attractive in comparison with its deposition in geological repositories (Harvard University, 2003). The literature has some example of analysis investigating the most preferable destination to the spent nuclear fuel. However, none of those analysis have been carried out considering Brazilian specific conditions which may be a future concern as there is the prospect of expanding the nuclear power supply of this country. This manuscript reports our efforts to understand the levelized cost of electricity generation aiming to establish a method for evaluating the economic viability of different destinations to spent nuclear fuel in Brazil.

2. LEVELIZED COST OF ELECTRICITY

Here we are interested on learning how to evaluate the economical differences between recycling or storaging used nuclear fuel accordingly with Ref. (Penalonga et al. 2016). For that evaluation we consider the levelized cost of electricity. The levelized cost electricity is the net present value of the unit-cost over the lifetime of a given facility and it is denoted *L*. Here *L* is decomposed into two components the front-end and back-end levelized costs, with the front-end components being the fuel used by the facilities. After the uranium is used in the reactor to generate electricity, it will go through several stages until it is permanently stored. These steps are back-end flames and include: temporary storage, reprocessing, recycling and final disposal. The front-end levelized cost is related with the costs of mining, converting, enrichment and manufactoring uranium into nuclear fuel and is denoted by L_1. The back-end costs are related with the initial investment and maintainence of the facility and will be indicated by L_2. Then we set *L* as

$$L = L_1 + L_2 . \tag{1}$$

To compute L_1 we consider the cost of the obtaining the assembled fuel for usage by the nuclear power plant per amount of generated power, namely $/MWh. That demands compute the costs of natural uranium mining (denoted by n_1), conversion (denoted by n_2), enrichment (denoted by n_3) and fuel manufacturing (denoted by n_4) and the costs of recycled uranium enrichment (denoted by r_1) and manufacturing fuel (denoted by r_2) when it is the case. Then L_1 becomes

$$L_1 = c_n \sum_{i=1}^{4} n_i + c_r \sum_{i=1}^{2} r_i \tag{2}$$

where the quantities c_n and c_r are the factors that have units kg/MWh and is used for converting the costs from \$/kg to \$/MWh.

We now compute L_2 and consider the calculus of net present values of investments, closure, maintainence and transport. We consider the following investments and costs related with the operation of a given power facility all given in monetary units \$. The investment of a given facility is the amount of capital initially employed to make it operational, it is denoted by *I*. The closure cost of the facility is the capital necessary for decomissioning the facility and is denoted by *C*. This analysis considers the following investments and costs generated by the facility with levelized present cost given by *L* with back-end costs denoted by L_1 and front-end costs, L_2. We indicate the investment, costs of closure, operation/maintenence and transport of a facility, respectively by *I, C, M* and *T*. Back-end investments are precified accordingly with a discount rate *i*. The *capital recovery factor* of invested capital on starting and closure of the facility is denoted by *r* and the *discount factor* for computing the present values of investments is indicated by *d*. And last the *conversion factor* of periodical costs for operating the facility are denoted by *s*. We write L_2 as

$$L_2 = r[(I + C)d + (M + T)s] \tag{3}$$

and L_2 as the summation of the costs of the fuels used for power production considering their price per kg and their electricity generation capacity in kg/kWh. *r* is computed considering that the return of the investiment is done by means of yearly periodical payments during the whole period *N* during which the facility generates profit and it is given by

$$r = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

and notice that one may compute the limit of *r* as *i* goes to zero considering the binomial of the component $(1+i)^N$. At this limit we have:

$$r_0 = \lim_{i \to 0} r = \frac{1}{N} \tag{5}$$

and r_0 is inversely proportional to *N*. The CRF is used to compute the present values of both the initial investments and operational costs of the facility. Now we consider the discount factor is a factor given by

$$d = \frac{1}{(1+i)^{t_0}} \tag{6}$$

which is used for computing the present value related to the complete time during which the power plant remains operational, which is indicated by t_0. And last we consider the costs during which the facility is operational which present value is computed using the conversion factor given by:

$$s = \frac{(1+i)^N - 1}{i(1+i)^N} \tag{7}$$

and those expenditures are mainly spent with operation, maintenance and transportation.

One inspecting the equation defining L_2 notices that the CRF is a factor multiplying each of its components and governs the value of L accordingly with the value of N. Therefore, to understand the behavior of L accordingly with the value CRF one may investigate its behavior accordingly with variations on N depending on the value of the discount rate i. We evaluae it considering the ratio R between the first order derivatives dr/dN and dr_0/dN that results

$$R = \frac{i(1+i)^N \ln(1+i) N^2}{[(1+i)^N - 1]} \tag{8}$$

and another element affecting L is the discount factor, given by d. Let us consider the condition for i not null and compare both r and d such that

$$\frac{r}{d} = \frac{i(1+i)^{t_0+N}}{(1+i)^N - 1} \tag{9}$$

which enables us to understand which factor between r and d is the most important on determining the back-end costs.

3. RESULTS

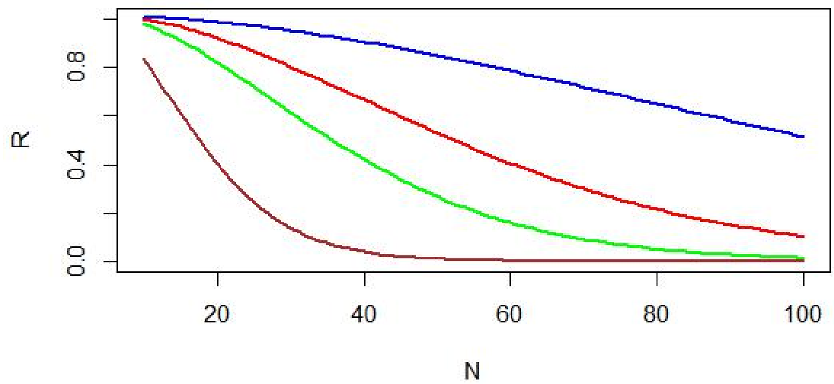

Figure 1: The values of R are plotted as function of *N* for multiple values of *i*, where *i* =0.03, 0.06, 0.09, 0.2 for lines of colors blue, red, green and brown, respectively. For $R(N,i) < 1$ we have that the CRF decreases faster when $i = 0$ than for $i \neq 0$. Note that for $i_1 < i_2 < i_3 < i_4$ and *N* fixed one has $R(N, i_1) > R(N, i_2) > R(N,i_3) > R(N,i_4)$.

Figure 1 shows some scenarios for the ratio *R*. Each line corresponds to a given discount rate and the horizontal axis has a variation on the operational time of the facility. *R* is smaller than one for all values of the discount rate and operational lifetime of the facility and it implies that the cost is less affected by a non-null discount rate. Although studies evaluating investiments on long term projects in general use a discount rate between 0 and 3% per year here we also consider the possibility of having *i*=6%, 9%, and the absolutely unrealistic 20% scenario. The latter has didatical purposes and helps us to understand how the cost stops being affected as the facility lifetime grows towards 100 years. The 6% discount rate per year may sound unreasonable but for Brazil it makes sense because the basic discount rate is currently 9.25% per year and the inflation acumulated during the last 12 months in Brazil is about 3%. Notice that the cost goes down whenever one has a longer lifetime for the facility. This analysis confirms that the longer the lifetime of a facility, the better it is.

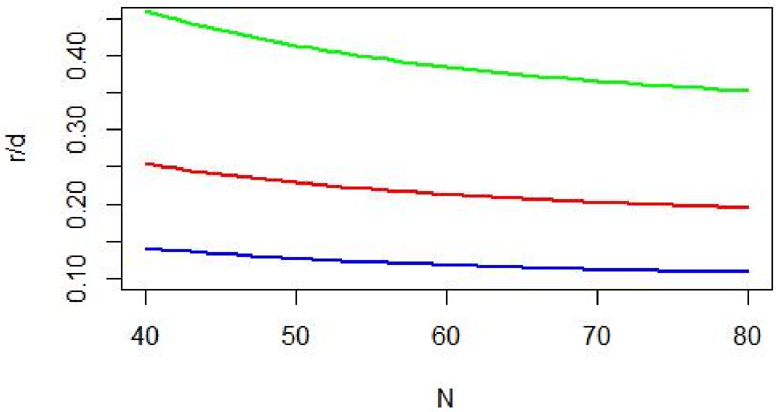

Figure 2: the ratio between the CRF and discount factor for non-null discount rate is shown. We consider *i*=3% per year and three different values for t_0=40, 60, 80 years being respectively indicated by the blue, red and green lines. Notice that the discount factor is greater than CRF for all values of t_0.

Figure 2 shows the comparison between CRF and the discount factor for a non-null discount factor *i.* That comparison helps to understand which of those factors has a stronger impact on levelized cost. Note that for the time range that we considered for the lifetime of the power facility and for the values of t_0 one has that CRF is always less important than the discount factor on determining L_2. A second aspect is that the importance of CRF is reduced if the value of *N* becomes greater than the importance of CRF on determining the levelized cost grows. Secondly, one may also investigate the importance of having $t_0<N$ or $t_0>N$ and the figure shows that the contribution of CRF falls faster for the first case than for the second. For example, if we consider t_0=40 years the influence of CRF falls slower than for the case when and the operational lifetime is 80 years. Indeed, that can be viewed algebraically by evaluating the first derivative of *r/d* in relation *N* which results into

$$-(1+i)^{t_0-N}\frac{i\ln(1+i)}{[1-(1+i)^{-N}]^2} \tag{10}$$

notice that *r/d* it is always negative and that term $(1+i)^{t_0-N}$ being greater than one increases the absolute value of the derivative for $t_0>N$ or reduces it otherwise.

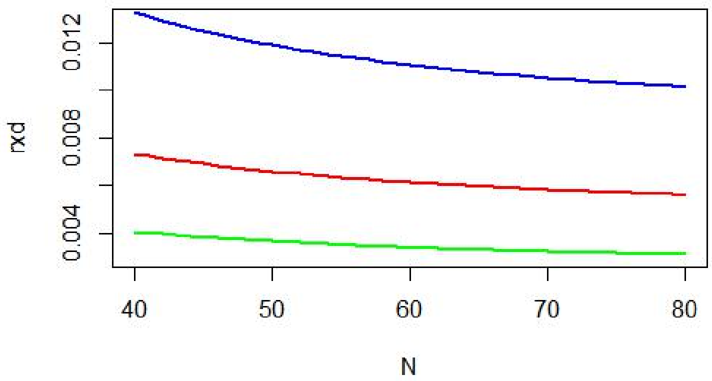

Figure 3: the product between the CRF and discount factor for non-null discount rate is shown. We consider *i*=3% per year and three different values for t_0=40, 60, 80 years being respectively indicated by the blue, red and green lines. Notice that the influence of this component on the levelized cost is reduced as t_0 increases.

Figure 3 shows the product between CRF and the discount factor and how it influences the levelized cost. Notice that it falls slowly accordingly with the increase of *N*. Notice that the higher the value of t_0 the smaller the cost and it is minimal for the condition when $t_0=N=80$ years. This is important because establishes the time for building the back-end facility as being the same as the power facility lifetime. However, if the back-end facility starts being operational during the power facility's lifetime, than the longer the power facility is operational the smaller is its impact on levelized cost as one may notice by inspection of the blue line.

4. CONCLUSION

In this manuscript we have presented our studies aiming to understand how the levelized cost analysis aiming to apply it for investigating the economical differences between storaging and recycling nuclear fuel. We have considered how the CRF and the discount factor affects the levelized cost of a given power facility. We also have implemented the computational machinery necessary for a comparative evaluation of economical costs involved on both storaging and recycling of spent nuclear fuel strategies. This is the next step that we are going to give on our project.

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REFERENCES

1. EASAC. "Management of spent nuclear fuel and its waste", https://ec.europa.eu/jrc/sites/jrcsh/files/jrc-report-anagement-spent-fuel-and-waste.pdf (2014).
2. Harvard University. "The ecnomics of reprocessing versus direct disposal of spent nuclear fuel", http://ocw.ateneo.net/courses/nuclear-engineering/22-812j-managing-nuclear-technology-spring-2004/readings/repro_report.pdf (2003).
3. IAEA-UN. "Spent Fuel Reprocessing Options", http://www-pub.iaea.org/MTCD/publications/PDF/te_1587_web.pdf (2008).
4. Idaho National Laboratory. "Nuclear fuel reprocessing", https://pdfs.semanticscholar.org/308f/ce889d24051681a9c53a06c856c38fc1bf1b.pdf (2010).
5. OECD. "The economics of the back-end of the nuclear fuel cycle", https://www.oecd-nea.org/ndd/pubs/2013/7061-ebenfc.pdf (2013).
6. OECD. "The economics of the nuclear fuel cycle", https://www.oecd-nea.org/ndd/reports/efc/EFC-complete.pdf (1994).
7. Penalonga, Laura Rodriguez et al . "Spent nuclear fuel management: levelized cost of electricity generation and analysis of various production scenarios", *Energies*, **9**, (2016).
8. Soria, B.Y.M.; Mas, M.U.; Estadieu, M.; Lejarreta, A.V.; Echevarria-López, D. "Recycling versus Long-Term Storage of Nuclear Fuel: Economic Factors", *Science and Technology of Nuclear Installations*. **2013**, (2013).
9. World Nuclear Association. "The nuclear fuel cycle", http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx (2017).