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AVALIAÇÃO DA ESTRATÉGIA DE GESTÃO DE COMBUSTÍVEL USADO NAS USINAS NUCLEARES DO BRASIL BASEADA NA METODOLOGIA MULTICRITÉRIO DE TOMADA DE DECISÕES

Bruno Estanqueira Pinho

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia Nuclear, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia Nuclear.

Orientador: José de Jesús Rivero Oliva

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AVALIAÇÃO DA ESTRATÉGIA DE GESTÃO DE COMBUSTÍVEL USADO NAS USINAS NUCLEARES DO BRASIL BASEADA NA METODOLOGIA MULTICRITÉRIO DE TOMADA DE DECISÕES

Bruno Estanqueira Pinho

Julho/2024

Orientador: José de Jesús Rivero Oliva

Programa: Engenharia Nuclear

Selecionar a melhor estratégia para combustível nuclear usado (SF) e os rejeitos de alta radioatividade (HLW) é um desafio mundial. Atualmente o Brasil não tem uma estratégia escolhida para a disposição final de SF e de HLW e não considera SF como HLW, devido à falta de decisão do governo em reprocessar ou não o SF, devido à enorme quantidade de energia dentro dele, mesmo depois de usado em um usina nuclear (NPP).

A proposta desta tese é uma nova metodologia para avaliar as possíveis estratégias para o futuro do SF gerado em um país, utilizando a *Analytical Hierarchy Process* (AHP), uma das ferramentas de análise de decisão multicritério mais utilizadas no mundo, quando uma decisão complexa precisa ser tomada, considerando múltiplos critérios e partes interessadas. A metodologia inclui uma avaliação adicional de custo das principais estratégias para complementar as informações necessárias para o processo de tomada de decisão.

O processo de validação foi realizado com a sua aplicação do cenário no Brasil, em um estudo de caso, considerando todos os principais critérios que precisam ser considerados, utilizando especialistas e partes interessadas no processo de gestão do SF no Brasil.

Abstract of Thesis presented to COPPE / UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

AN APROACH FOR EVALUATION OF THE SPENT NUCLEAR FUEL MANAGEMENT STRATEGY FOR BRAZILIAN NUCLEAR POWER PLANTS BASED ON MULTICRITERIA DECISION MAKING METHODOLOGY

Bruno Estanqueira Pinho
July/2024

Advisor: José de Jesús Rivero Oliva

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Selecting the best strategy for Spent Nuclear Fuel (SF) and High-Level Radioactive Waste (HLW) is a worldwide challenge. Nowadays Brazil does not have a chosen strategy for SF and HLW disposal and do not consider SF as HLW, due to a lack of decision from the Government to reprocess or not the SF, due to the huge amount of energy inside of it, even after been used in a nuclear power plant (NPP).

This thesis proposal is a new methodology to evaluate the possible strategies for the future of SF generated in a country, using the Analytical Hierarchy Process (AHP), one of the most used multicriteria decision analysis tools in the world, when a complex decision needs to be taken considering multiple criteria and stakeholders. The methodology includes additional cost evaluation of the main strategies to complement the information needed for the decision-making process.

The validation process was executed with the application to Brazil´s scenario, in a case study, considering all the main criteria that need to be considered, using experts and stakeholders involved in the process of SF management in Brazil.

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LIST OF ABBREVIATIONS AND ACRONYMS

ALARA	As Low As Reasonably Achievable
ANSN	National Nuclear Safety Authority
CBO	Congressional Budget Office of United States
CDTN	Centro de Desenvolvimento da Tecnologia Nuclear
CFC	Closed Fuel Cycle
CNAAA	Almirante Alvaro Alberto Nuclear Center
CNEN	Brazilian Nuclear Energy National Commission
DM	Decision Making
DOE	United States Department of Energy
DTF	Decommissioning Trust Fund
EASAC	European Academies' Science Advisory Council
EPE	Energy Research Enterprise
EPRI	Electric Power Research Institute
ETN	Eletronuclear S.A.
EURATOM	European Atomic Energy Community
EW	Exempt Waste
FSAR	Final Safety Analysis Report
GD	Geological Disposal
GDF	Geological Disposal Facility
HIDAwi	Hindawi Publishing Corporation
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IBAMA	Brazilian Institute of the Environment and Renewable Natural Resources
ILW	Intermediate Level Waste
INB	Indústrias Nucleares do Brasil
INPO	Institute of Nuclear Power Operation

ISFSI	Independent spent fuel storage installation
LBNL	Lawrence Berkeley National Laboratory
LCO	Limiting Condition for Operation
LLW	Low Level Waste
LTO	Long-Term Operation
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Method
MLW	Medium Level Waste
MWe	Electric Megawatts
MWt	Thermal Megawatts
NEA	Nuclear Energy Agency
NFC	Nuclear Fuel Cycle
NMSS	Nuclear Material Safety and Safeguards
NPP	Nuclear Power Plant
O&M	Operational & Maintenance
OECD	Organization for Economic Co-operation and Development
OFC	Open Fuel Cycle
pDCE	Preliminary Decommissioning Cost Estimate
PDP	Preliminary Decommissioning Plan
PHWR	Pressurized Heavy Water Reactors
PNE	Brazilian National Energy Plan
Pu	Plutonium
PWR	Pressurized Water Reactor
RepU	Reprocessed Uranium
RR	Research Reactor
RW	Nuclear Radioactive Waste
RWMC	Radioactive Waste Management Center
SAFSTOR	Safe Storage
SF	Spent Nuclear Fuel

SFM	Spent Fuel Management
SFP	Spent Fuel Pool
tHM	Tons of heavy metal
TP	Transition Period
TS	Technical Specification
U.S.NRC	United States Nuclear Regulatory Commission
UAS	ISFSI Dry Storage Installation at CNAAA
UFRJ	Rio de Janeiro Federal University
USA	United States of America
VLLW	Very Low-Level Waste
VSLW	Very short-lived waste
WEC	Westinghouse Electric Company or Westinghouse
WMB	Waste Monitoring Building
WNA	World Nuclear Association

1. Introduction

1.1. Preface

In the twenty-first century the world will need increasing supplies of electricity to maintain economic growth, particularly with a growing global population and increasing industrialization in the developing nations.

Until 2050, global energy consumption is projected to increase by about 30% and it is also becoming clear that a major effort will be needed to decarbonize our energy supplies. Against this background, even after Fukushima earthquake event, there is a renewed interest in nuclear energy as it has the potential to provide large quantities of secure, low-carbon energy, as stated in International Energy Agency's Net Zero by 2050 report [WNA, 2022].

However, nuclear technology raises questions, related to the management of the high-level radioactive waste (HLW) and spent nuclear fuel (SF), and how to deal with them from past, present and future generation's reactors. Some questions appear to be unresolved, what generates debate about the long-term sustainability of nuclear energy as a contribution to a low carbon energy supply in numerous countries, while reducing greenhouse gas emissions is a worldwide priority [IAEA, 2021; OECD/NEA, 2020; EASAC, 2014].

A well stablished SF and Radioactive Waste (RW) management for the country is critical for the sustainability of nuclear energy [WNA, 2022]. Main issues regarding the expansion of nuclear energy are: 1. Non-proliferation of nuclear weapons (security), 2. Nuclear Safety (nuclear accidents), 3. Radioactive wastes disposal and management, and 4. Environmental Impact. Having those issues strategically managed is needed for nuclear industry expansion. Some of the main factors that influence countries in choosing their spent fuel management strategy are usually related to political/social aspects, economics, national strategy, environmental impact, and non-proliferation/security considerations [WNA, 2022; TAYLOR, J. ROBIN et al, 2015, IAEA, 2022].

Managing SF generated from the production of electricity in nuclear power plants, until its disposal is an important step of the nuclear fuel cycle. While one third of the spent fuel accumulated globally is reprocessed, most of it is stored until a decision is taken on the end-point strategy (processing or disposal). The challenges are to identify and address relevant technological issues as well as to maintain a certain flexibility in the SF management (SFM) to accommodate the largest range of potential options for the future [IAEA, 2021; OECD/NEA, 2020; EASAC, 2014].

The nuclear fuel cycle (NFC) ends with the safe, secure and sustainable management of the spent fuel, which includes its storage after withdrawal from the core of the nuclear power plant (NPP), followed by either its processing/recycling or final disposal. Safe, secure, proliferation resistant and economically efficient NFCs that minimize waste generation and environmental impacts globally contribute to the sustainability of nuclear energy [IAEA 2019; IAEA 1, 2021; EASAC, 2014].

Essentially, two options exist: either dispose of the spent fuel after containment in a suitable waste form in a waste repository (the “open” or “once-through” fuel cycle option) or separate out the reusable components for recycling, disposing of the residual waste products only (the “closed” fuel cycle option). Many countries have adopted the open fuel cycle in which spent fuel is to be stored and then moved to a geological disposal facility (GDF) as soon as one is available. However, despite significant progress now being made in a few countries, especially Sweden and Finland, no country has yet opened a GDF for SF disposal [TAYLOR, J. ROBIN et al, 2015; IAEA, 2022].

The amount of spent fuel, therefore, being interim stored rather than disposed of or reprocessed and recycled, is growing. Simple estimates suggest that, if nothing else is done, there could be over a million tons of spent fuel in interim storage worldwide by 2100 [TAYLOR, J. ROBIN et al, 2015; IAEA, 2022].

The safe, secure, reliable, and economic management of SF arising from nuclear power reactors is key for the sustainable utilization of nuclear energy and covers many technological aspects related to the storage, transportation, and disposal of the SF and HLW generated from recycling through its reprocessing [IAEA, 2019].

The implementation of any selected strategy can take decades, and national strategies should be flexible enough to make it possible to accommodate potential future options and new technologies that will enhance and improve the safety and sustainability of nuclear power. Allocating the necessary resources to implement the strategy is difficult. Several national strategies reflect the need to make available sufficient SF storage capacity to bridge the gap between the generation of SF and the foreseen commissioning and operation of deep geological disposal facilities. The industry continues to develop safe technologies for long term fuel storage [IAEA, 2021].

Timeline for a country to take a decision regarding SFM is critical. In Finland´s SF repository, it was planned to be operational until 2024 (started construction in 2016), 24 years after site selection and more than 40 years of research [NEI, 2023]. In Sweden, in January of 2023 it has been issued the licensing approval for starting their SF repository construction, also after 40 years of research and they are planning 10 years until it becomes operational [SKB, 2023].

Considering that Finland and Sweden have the most developed projects of SF repository under implementation, Brazil would take at least 40 to 50 years to develop its own project or around 20 years if the technology be brought from another country or company, as many steps will have to be prepared before stating construction, such as site selection, specification and purchase process, licensing, etc., so start thinking about SF future is needed.

Brazil is struggling for more than 20 years with the planning and construction of its first low and intermediate level waste repository that used to be called RBMN (National Repository for LLW and ILW) and now is called CENTENA (Nuclear and Environmental National Technology Center) and still have not concluded the site selection for construction and has no planned operation date [CDTN, 2023]. Therefore, it is very important for Brazil to take a strategic decision regarding SF and starting to plan its Disposal to ensure the sustainability of nuclear energy in the country.

Considering the global scenario there is an increasing number of reactors reaching close to its decommissioning, 17 that have been fully dismantled, over 50 are being dismantled and over 50 in safe storage [WNA, 2021]. Hence, the need of a clear SF strategy worldwide is critical for the next nuclear generation. In the same way, Brazil needs a SF management and HLW disposal discussion to support new NPPs construction.

Nowadays Brazil has two operating Nuclear Power Plants (NPPs), Angra 1 and 2, producing together around 2 gigawatts (GW). Brazil has also a third NPP, called Angra 3, that had its construction stopped in 2015 with 67,1% of civil scope executed, and have restarted in 2022, with 1,4GW more, and is planned to be operating until 2028 [ELETRONUCLEAR, 2022; CNN, 2021].

Also, according to Brazilian National Energy Plan 2050 (PNE 2050) it is planned to be installed more NPPs in Brazil to reach between 4GW to 8GW until 2030 and 8GW to 10GW until 2050 [EPE, 2021]. Therefore, the country needs a National Spent Fuel Policy and Strategy to keep nuclear energy development and growth.

Besides that, Brazil has still not come into a decision regarding SF destination and the need of a profound study and analysis of what to do with HLW and SF is increasing and extremely important for the future generations and to support nuclear energy development in the country [CNEN, 2017]. Brazil needs to decide which path to take, considering direct disposal, long term storage and reprocessing options.

1.2. Purpose

The objective of this research is to contribute to the sustainability of the nuclear power generation activity, by developing a methodology based on Multi Criteria Decision Method (MCDM) to evaluate SF and HLW management strategy to support the decision of which path to follow for a country with operating NPPs. Also, there are described the best practices worldwide in the MCDM and criteria selection. The method selected and criteria will be useful to support the decision-making process for the Brazil specific scenario as no decision has been taken regarding SF disposal in the country and complemented with a preliminary cost evaluation of each one. The specific objectives are to:

a) Describe how is the worldwide scenario related to the nuclear fuel back end, and Brazil´s situation, with decommissioning background, RW and SF management, disposal options, open and closed NFC.
b) Identify which are the most used MCDM used to evaluate SF Management options and the most used and relevant criteria that need to be considered, according to international experience and research.
c) Identify the possible options/scenarios for SFM in Brazil
d) Evaluate Brazil´s SF management options with the selected MCDM and using specialists' opinions to rank each one according to the selected criteria.
e) Prepare a cost estimative of the main options to complement the evaluation of the research.
f) Rank the best strategies regarding SF management in Brazil to assess the decision-making process.

1.3. Relevance

The absence of spent fuel disposal facilities compromises the credibility of the nuclear community and reduces public acceptance of current and future nuclear programs. Defining a policy for the management of SF and RW is an essential cornerstone to ensure continuity in the necessary technological developments and related investments, and the consolidation of knowledge. The safe, secure and sustainable management of spent fuel from nuclear power reactors is key to the future of nuclear energy [RATIKO et al, 2020; EASAC, 2014; IAEA, 2019].

Today, besides the growth of nuclear energy generation in Brazil predicted in Brazilian National Energy Plan 2050 (EPE, 2021), the country still has not selected a strategy for its HLW and SF generated. A clear strategy is needed and an analysis of alternatives for SF and HLW destination is critical for nuclear energy development and increase in the country with sustainability. So far, Brazil still does not consider SF as RW as the country has not reached to a national decision about the future of SF and how it will be managed. The policy in Brazil is described in the National Report of Brazil 2017 for the Joint Convention on the Safety of SF management and on the safety of RW management [CNEN, 2017], as follows:

“The policy adopted regarding spent fuel from nuclear power plants is to keep the fuel in safe storage until a technical, economic, and political decision is reached about reprocessing and recycling the fuel or disposing of it as such. It should be highlighted that, by the federal Brazilian legislation, spent fuel is not considered radioactive waste. Therefore, in the scope of this Convention, spent fuel will be not considered as such” [CNEN, 2017].

Decree Nº. 9,600 of December 5, 2018, consolidates the guidelines on the Brazilian Nuclear Policy and establishes that spent fuel is not considered a radioactive waste and must be stored for future reuse, until country decision.

The most hazardous portion of the waste is spent nuclear fuel. On average, the global SNF stockpile increases by 11,300 tons of heavy metal (tHM), generated by almost 450 operational nuclear power reactors worldwide [STIMSON, 2022]. Brazil, with 2 operating units (Angra 1 and 2), Angra 3 under construction, and more 8 extra GW of energy planned until 2050 [EPE, 2021] needs urgently to define a clear Spent Fuel Management Strategy.

Therefore, the relevance of this thesis is to support a government decision of which is the best path for the Nuclear Spent Fuel generated by nuclear power plants in Brazil and provide nuclear energy generation safe and sustainable growth in the country.

1.4. Originality

Spent Nuclear Fuel disposal and management in Brazil have been studied and discussed from multiples perspectives, as site selection, storage and disposal, reprocessing, transportation, thermal analysis, cost estimation, safety analysis [MARTINS, 2009; JONUSAN, 2021; NODARI et al, 2020; OSTI, 2016, ROMANATO, 2005].

To the best of author´s knowledge, this thesis would be the first open-source publication in Brazil to face the SFM Strategy, proposing a multi criteria methodology oriented to decision making and based on an extensive research work to identify and weigh the most relevant criteria that need to be evaluated. The application case for the Brazilian scenario, complemented with preliminary cost estimate, will support the country’s decision of which strategy to follow regarding the future of SF.

The absent of more detailed study of the Brazilian SF strategy could be one of the reasons of lack of decision regarding it in the country.

1.5. Motivation

Defining a spent fuel management policy is an essential step and each country managing a nuclear energy program must ensure that the necessary technical and financial resources are available now and, in the future [IAEA 1, 2021; EASAC, 2014].

To date the progress towards commissioning deep geological disposal facilities is slow, although several projects are in an advanced stage of development to meet this goal. Spent fuel storage systems may therefore have to be maintained for longer periods of time, possibly for more than 100 years, which induces research and development to be carried out and ageing management program to be established to demonstrate the safety case of long term spent fuel storage [IAEA, 2022].

A stable spent fuel management (SFM) policy is thus needed for the long timeframes envisaged. This can only be achieved with the strong involvement of policy makers, governmental organizations, regulatory bodies, operators, spent fuel and radioactive waste management organizations, and the industry. Ensuring responsible and safe management of radioactive waste and spent fuel to avoid undue burdens on future generations reaffirms the principles of prime responsibility of license holders for the safety of this management, under the supervision of the national competent regulatory authority, and of ultimate responsibility for the management of the radioactive waste and spent fuel generated [IAEA, 2022; EURATOM, 2015].

So far, even with all the international recommendations of having a clear and defined plan for managing SF and HLW, Brazil still does not have a policy for that and has not reached to a decision of which path is the best to follow.

This thesis intends to support the decision regarding scenarios and options for the destination of SF and HLW by developing a well-structured MCDM evaluation, to assist nuclear energy growing with sustainability.

Additionally, during the environmental licensing process of Angra 3 NPP, two environmental requirements have been issued related to management of the Brazilian SF management:

- Requirement 2.18 of Preliminary License 279/2008 [IBAMA, 2008], which determined "To present a proposal and start the execution of the project approved by the environmental agency for final disposal of high-activity radioactive waste before the start of operation of Unit 3”.

- Requirement 2.20 of Installation License 591/2009 (IBAMA, 2009), which determined: "To present in 180 days a technical-financial and execution schedule according to the analytical structure of the RAN Project - Long Term Waste Deposit for used fuels, approved by CNEN".

Furthermore, not having definition about the nuclear cycle model to be followed and, consequently, the lack of a formal policy and strategy for SFM in Brazil, result in several deficiencies, as lack of criteria for the selection of the final disposal sites for SNF, and lack of provision or financial reserve by its generator. As stated in the Inspection report of the Agreement 1,108 / 2014 of Brazilian Federal Court of Auditors [TCU, 2022]:

"The lack of a formal policy and strategy on the management of nuclear spent fuel in national territory, with the absence of a solution to be adopted in the country (direct disposal, reprocessing or waiting for technological/economic maturation of the available options), may harm the fulfillment of the obligations assumed by Brazil through the caput and items of Article 4 of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, promulgated by Decree No. 5,935, of 2006, in addition to constituting an important risk to the nuclear fuel management process used in the country”.

These TCU requirements must be answered to have Angra 3 NPP starting its operation and this thesis will also help to increase knowledge on SFM and the country to define the best SFM strategy based on a methodology using multi-criteria method applied to Brazil scenario.

1.6. Assumptions

This thesis is limited to the following assumptions:

1. Only SF and HLW generated by the NPPs at Angra facility will be considered, as the NPPs represents the greatest amount of the mentioned nuclear material generated in the country.
2. It will not be considered SF generated from Research Reactors (RR), as their volume is irrelevant if compared with the whole volume of the SF generated from Nuclear Power Reactors according to “Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management” report [CNEN, 2020], neither from the future SF from the planned nuclear powered Brazilian submarines as their volume are irrelevant compared with the generated from Nuclear Power Reactors.
3. Only information available on open sources will be used.
4. Although the scenario in the National Energy Plan PNE2050 [EPE, 2021] is described considering 8 more NPP until 2050, it has been considered only Angra 1 NPP, Angra 2 NPP and Angra 3 NPP in operation, as the more credible scenario to evaluate the methodology.

2. Literature Review

This chapter describes the literature regarding decommissioning, SF management, reprocessing, and storage, RW management and its disposal, and Multicriteria Decision Method Techniques supporting the decision-making process.

2.1. Decommissioning Background

All power plants, coal, gas and nuclear, have a finite life beyond which it is not economically feasible to operate them. Usually, early nuclear plants were designed for a life of about 30 years, though with refurbishment, some have proved capable of continuing well beyond this. Newer plants are designed for a 40-to-60-year operating life. At the end of the life of any power plant, it needs to be decommissioned, cleaned up and demolished so that the site is made available for other uses. For nuclear plants, the term decommissioning includes all clean-up of radioactivity and progressive dismantling of the plant [WNA, 2021]

According to United States Nuclear Regulatory Commission (U.S.NRC), Decommissioning of a Nuclear Power Plant means the process of safely closing a nuclear power plant (or other facility where nuclear materials are handled) to retire it from service after its useful life has ended. This process primarily involves decontaminating the facility to reduce residual radioactivity and then releasing the property for unrestricted or (under certain conditions) restricted use. This often includes dismantling the facility or dedicating it to other purposes. Decommissioning begins after the nuclear fuel, coolant, and RW is removed [U.S.NRC, 2019].

2.1.1. Strategies for decommissioning

According to International Atomic Energy Agency (IAEA) [IAEA GSR Part 6, 2014], two possible decommissioning strategies are applicable: immediate dismantling and deferred dismantling, as follows:

- ✓ Immediate dismantling, when decommissioning actions begin shortly after the permanent shutdown. Equipment and structures, systems and components of a facility containing radioactive material are removed and/or decontaminated to a level that permits the facility to be released from regulatory control for unrestricted use or released with restrictions on its future use.

- ✓ Deferred dismantling, when after removal of the nuclear fuel from the facility (for nuclear installations), all or part of a facility containing radioactive material is either processed or placed in such a condition that it can be put in safe storage and the facility maintained until it is subsequently decontaminated and/or dismantled. The NPPs in this case, stay long periods in safe enclosure (period during the implementation of the deferred dismantling strategy in which the facility is placed and maintained in a safe, long term storage condition until decontamination and dismantling actions are performed [IAEA GSR Part 6, 2014].

Generally, immediate dismantling is the preferred strategy, as it avoids transferring the burden of decommissioning to future generations. The immediate dismantling strategy should be understood as immediate and complete dismantling in a timely manner, with no delay in decommissioning. Release from regulatory control without restrictions should be the preferred end state and ultimate objective of decommissioning. No action (leaving the facility after operation as it is and waiting for decay of the radioactive inventory) and entombment (encasing all or part of the facility in a structurally long-lived material) are not acceptable decommissioning strategies [IAEA SSG-47, 2014; IAEA GSR Part 6, 2014].

A combination of these two strategies (Immediate/deferred dismantling) may be considered practicable considering safety or environmental requirements, technical aspects, and local conditions, such as the intended future use of the site, or financial considerations. Entombment, in which all or part of the facility is encased in a structurally long-lived material, is not considered a decommissioning strategy and is not an option in the case of planned permanent shutdown. It may be considered a solution only under exceptional circumstances (e.g., following a severe accident) [IAEA SSG-47, 2014; IAEA GSR Part 6, 2014].

2.1.2. Desired end state

The foreseen end states for different strategies are shown in Figure 1 [adapted from IAEA SRS-50, 2007; IAEA GSR Part 6, 2014].

An important consideration when selecting the decommissioning strategy is the desired end state of the facility following completion of the decommissioning. The preferred end state would be to achieve a situation whereby the site is released for unrestricted use (with or without buildings) or a situation whereby it may be released for restricted use. Other end states could involve partial release of a site or release of a site under restricted conditions to control its future use.

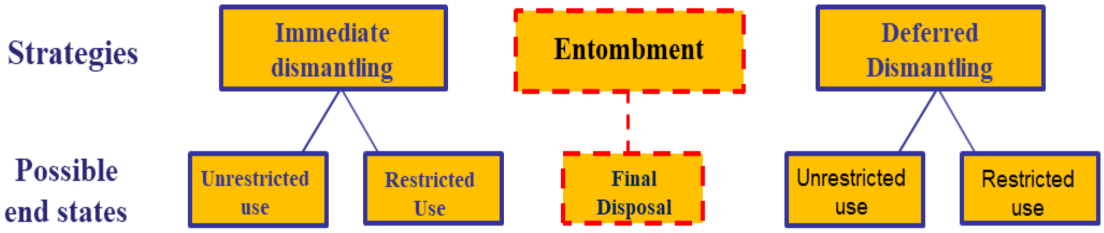


Figure 1 – Possible end states for the use of areas in the three decommissioning strategies

2.1.3. NPP´s Decommissioning Strategy in Brazil

Brazil has two operating nuclear power plants: Angra-1, 640 MWe gross, 2-loop PWR and Angra-2, 1,350 MWe gross, 4-loop PWR. The construction of the third plant (Angra-3, 1,405 MWe gross expected, 4-loop PWR) was stopped in September 2015, and it restarted in 2022. Angra-1, 2 and 3 are in a common site, near the city of Angra dos Reis, about 130 km south of the city of Rio de Janeiro [CNEN, 2017; CNN, 2021].

The three NPPs are located at the Central Nuclear Almirante Alvaro Alberto (CNAAA) site and are operated by Eletronuclear S.A. (ETN), a state holding company for the electric system in Brazil.

The CNAAA site has also a Radioactive Waste Storage Center (RWMC) with three buildings and one Waste Monitoring Building (WMB), an Independent Spent Fuel Storage Installation (ISFSI) under construction (turnkey project with Holtec International), and some support buildings and laboratories. Figure 2 [PINHO, 2018] shows the site of CNAAA, and all the support buildings related to waste and spent fuel management.

Figure 2 – Central Nuclear Almirante Alvaro Alberto – CNAAA - site

In Brazil, the National Nuclear Energy Commission (CNEN) is the regulatory body which obligates the NPPs to have a decommissioning plan with basic requirements of nuclear safety to be achieved on planning and implementation of decommissioning and to manage the decommissioning financial resources according to the regulations CNEN NN 9.01 [CNEN, 2012] and CNEN NN 9.02 [CNEN, 2016].

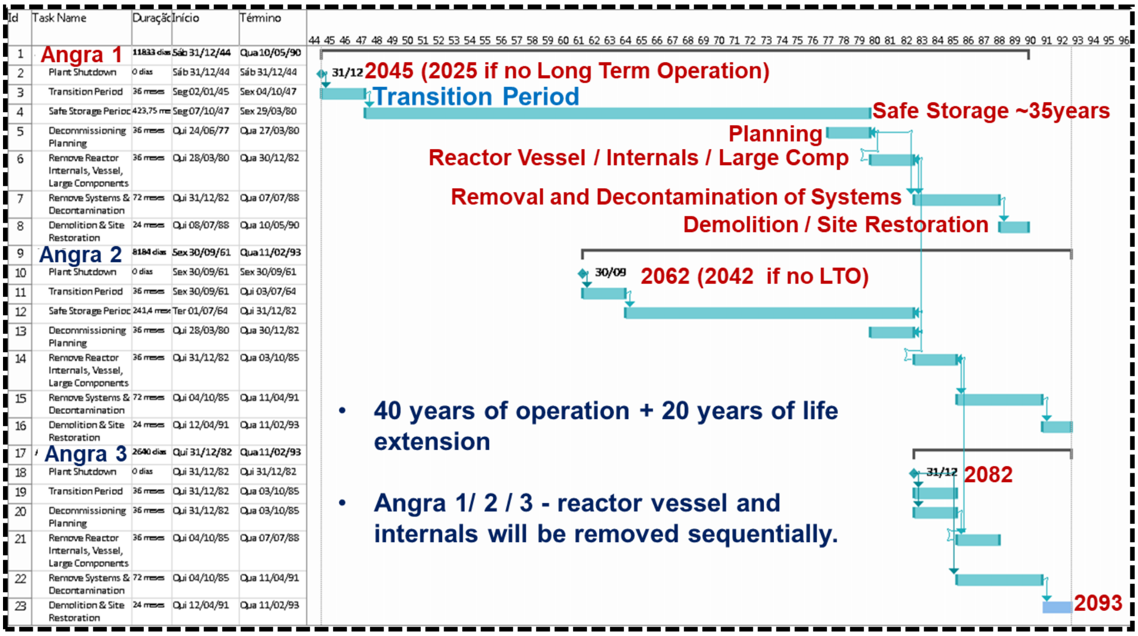
Since October 10th of 2021, the licensing of nuclear installations and their safety, safeguards and security is the responsibility of the Brazilian National Nuclear Safety Authority (ANSN) (Law 14.222/2021), but the regulatory actions are still being executed by CNEN, until ANSN starts its operations, when CNEN will keep operating the actual research institutes and laboratories that they coordinate.

2.1.3.1. Preliminary Decommissioning Plan (PDP) of CNAAA

The Preliminary Decommissioning Plan (PDP) of the CNAAA stablishes deferred dismantling for Angra 1 and 2 and Immediate Dismantling for Angra 3. The desired end State planned for each NPP is to be released with “unrestricted use” [ELETRONUCLEAR, 2019]. The CNAAA is a multiple plant site with dates of operation start very different, with Angra 1 starting operations in 1985, Angra 2 in 2000 and Angra

3 planned to start in 2026. Figure 3 [PINHO, 2018] shows a resumed schedule for the Decommissioning Strategy for CNAAA site.

It shows the planned decommissioning dates of Angra 1, 2 and 3 in the PDP of CNAAA, considering Long Term Operation (LTO) for all the plants. During operations and mainly after shutdown, the lack of definition of SF strategy has huge cost on the operation of the plants as there will be the need of keep building initial dry storage for the SF until Government reaches to a decision of where to send SF.



Id	Task Name	Duraçãc	Início	Término
1	**Angra 1**	**11833 dias**	**Sáb 31/12/44**	**Qua 10/05/90**
2	Plant Shutdown	0 dias	Sáb 31/12/44	Sáb 31/12/44
3	Transition Period	36 meses	Seg 02/01/45	Sex 04/10/47
4	Safe Storage Perioc	423,75 me	Seg 07/10/47	Sex 29/03/80
5	Decommissioning Planning	36 meses	Qui 24/06/77	Qua 27/03/80
6	Remove Reactor Internals, Vessel, Large Components	36 meses	Qui 28/03/80	Qua 30/12/82
7	Remove Systems & Decontamination	72 meses	Qui 31/12/82	Qua 07/07/88
8	Demolition & Site Restoration	24 meses	Qui 08/07/88	Qua 10/05/90
9	**Angra 2**	**8184 dias**	**Sex 30/09/61**	**Qua 11/02/93**
10	Plant Shutdown	0 dias	Sex 30/09/61	Sex 30/09/61
11	Transition Period	36 meses	Sex 30/09/61	Qui 03/07/64
12	Safe Storage Perioc	241,4 mes	Ter 01/07/64	Qui 31/12/82
13	Decommissioning Planning	36 meses	Qui 28/03/80	Qua 30/12/82
14	Remove Reactor Internals, Vessel, Large Components	36 meses	Qui 31/12/82	Qua 03/10/85
15	Remove Systems & Decontamination	72 meses	Qui 04/10/85	Qua 11/04/91
16	Demolition & Site Restoration	24 meses	Qui 12/04/91	Qua 11/02/93
17	**Angra 3**	**2640 dias**	**Qui 31/12/82**	**Qua 11/02/93**
18	Plant Shutdown	0 dias	Qui 31/12/82	Qui 31/12/82
19	Transition Period	36 meses	Qui 31/12/82	Qua 03/10/85
20	Decommissioning Planning	36 meses	Qui 31/12/82	Qua 03/10/85
21	Remove Reactor Internals, Vessel, Large Components	36 meses	Qui 04/10/85	Qua 07/07/88
22	Remove Systems & Decontamination	72 meses	Qui 04/10/85	Qua 11/04/91
23	Demolition & Site Restoration	24 meses	Qui 12/04/91	Qua 11/02/93

- **40 years of operation + 20 years of life extension**
- **Angra 1/ 2 / 3 - reactor vessel and internals will be removed sequentially.**

Figure 3 – CNAAA Decommissioning schedule resume.

2.2. Nuclear Radioactive Waste and Spent Fuel Management

Radioactivity is a natural phenomenon, and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry, and agriculture. The radiation risks to workers, public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled [IAEA GSG-7, 2018].

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to safety standards [IAEA GSG-1, 2009].

Nuclear Radioactive Waste (RW), for legal and regulatory purposes, are material for which no further use is foreseen that contains, or is contaminated with, radionuclides at activity concentrations greater than clearance levels as established by the regulatory body [IAEA Safety Glossary, 2018].

At various steps in the predisposal management of radioactive waste, the radioactive waste shall be characterized and classified in accordance with requirements established or approved by the regulatory body [IAEA GSR Part 5, 2009].

In their physical properties, radioactive wastes are either solid, liquid, gaseous or concentrates. During the operation of a reactor, different types of radioactive waste are generated, the main wastes arising during the operation of a nuclear power plant are components which are removed during refueling or maintenance or operational wastes such as radioactive liquids, filters, and ion-exchange resins which are contaminated with fission products from circuits containing liquid coolant. Solid radioactive waste can be contaminated equipment, clothes, tools, etc. Active liquid wastes are usually generated by the cleanup of primary coolants, cleanup of the spent fuel storage pond, drains, wash water, and leakage waters. Regarding gaseous radioactive waste, the main RW generated in during normal operation of nuclear power plants, are halogens, noble gases, tritium, and carbon-14.

At the end of its operating life, a reactor is shut down and eventually dismantled. During dismantling, contaminated and activated components are separated, treated and if necessary managed as radioactive waste [IAEA NW-T-1.14, 2022].

Radioactive Waste Classification is divided in six classes as follows [IAEA GSG-1, 2009; IAEA NW-T-1.14, 2022]:

(1) Exempt Waste (EW): Waste that meets the criteria for clearance, exemption, or exclusion from regulatory control for radiation protection purposes as described in Ref. [IAEA RS-G-1.7, 2004], where are defined the concepts of exclusion, exemption and clearance. Although the term ‘exempt waste’ has been given, for understanding, once such waste has been cleared from regulatory control, it is not considered radioactive waste [IAEA GSG-1, 2009; NW-T-1.14, 2022].

(2) Very Short-Lived Waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes [IAEA GSG-1, 2009; NW-T-1.14, 2022].

(3) Very Low-Level Waste (VLLW): Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in VLLW are generally very limited [IAEA GSG-1, 2009; NW-T-1.14, 2022].

(4) Low Level Waste (LLW): Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration [IAEA GSG-1, 2009; NW-T-1.14, 2022].

(5) Intermediate Level Waste (ILW): Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred meters [IAEA GSG-1, 2009; NW-T-1.14, 2022].

(6) High Level Waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred meters or more below the surface is the generally recognized option for disposal of HLW [IAEA GSG-1, 2009; NW-T-1.14, 2022].

High level waste is defined to be waste that contains such large concentrations of both short and long-lived radionuclides that, compared to ILW, a greater degree of containment and isolation from the accessible environment is needed to ensure long term safety. Such containment and isolation are usually provided by the integrity and stability of deep geological disposal, with engineered barriers. HLW generates significant quantities of heat from radioactive decay, and normally continues to generate heat for several centuries. Heat dissipation is an important factor that has to be taken into account in the design of geological disposal facilities.

One of the major problems facing the nuclear industry is the safe disposal of nuclear waste, particularly the 'high-level' wastes, some of which remain radioactive for hundreds of thousands of years. Because of toxicity and long half-lives, management of high-level nuclear waste is the most challenging problem in radioactive waste management [SAATY and GHOLAMNEZHAD, 1982].

High level waste (HLW), including spent fuel (SF) if declared as waste, is characterized by large concentrations of both short and long-lived radionuclides, so that a high degree of isolation from the biosphere (e.g., geological disposal) is needed to ensure long term safety. It generates significant quantities of heat from radioactive decay, and normally continues to generate heat for several centuries [IAEA TRS390, 1998].

An exact boundary level between LILW and HLW is difficult to establish without precise planning data for many parameters such as the type of radionuclide, the decay period and the conditioning techniques. Typical activity levels are in the range 5×10^4 to 5×10^5 TBq/m3, corresponding to a heat generation rate of about 2–20 kW/m^3 for decay periods of up to about ten years after discharge of spent fuel from a reactor. From this range, the lower value of about 2 kW/m^3 is considered reasonable to distinguish HLW from other radioactive waste classes, based on the levels of decay heat emitted by HLW, such as those from reprocessing spent fuel [IAEA TRS390, 1998].

Figure 4 [IAEA RS-G-1.7, 2004] illustrates the waste classification according to its activity and Half-life. It also shows which is the recommended disposal path for each waste stream, as deep geological disposal (HLW), intermediate depth disposal (ILW), LLW (near surface disposal), VLLW (landfill disposal) and decay storage (VSLW could wait in a decay storage facility). It can be clearly seen that HLW Is the most critical waste stream of all of them, with higher activity, although the biggest volume of waste generated is classified as VLLW and LLW (around 95%), with approximately 4% of ILW and 1% of HLW [IAEA NW-T-1.14, 2022].

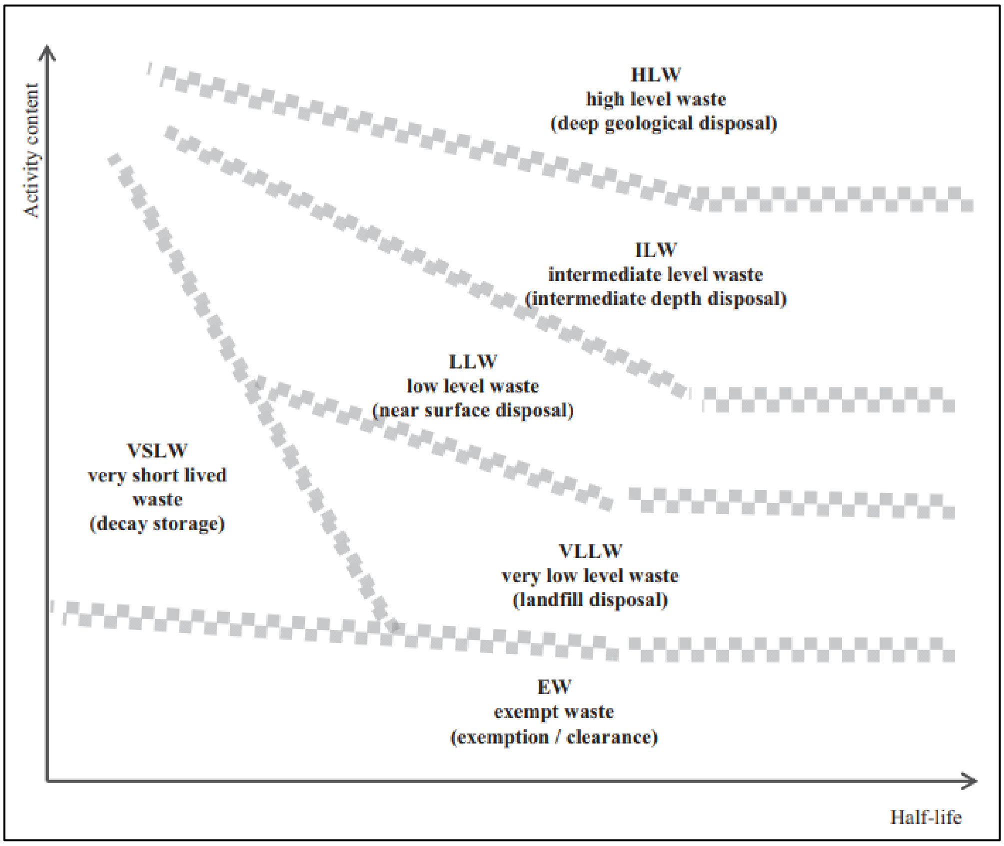


Figure 4 – Conceptual Illustration of waste classification

2.2.1. Radioactive waste from nuclear power plants

Typically, RW from a NPP includes gaseous, liquid, solid waste, spent fuel declared as waste and waste from its decommissioning.

Gaseous radioactive waste - Depending on the type of NPP, possible sources of gaseous radioactive waste include the following: (a) Leakage from the coolant; (b) The moderator systems of the reactor itself; (c) Degasification systems for the coolant; (d) Condenser vacuum air ejectors or pumps; (e) The exhaust from turbine gland seal systems; (f) Activated or contaminated ventilated air [IAEA SSG-40, 2016].

For all types of nuclear power plant, spent fuel in storage or in handling operations is a potential source of gaseous radioactive waste.

Liquid radioactive waste - The primary coolant in water-cooled reactors and water from the fuel storage pools are major sources of liquid radioactive waste, as some of their radioactive content may be transported to the liquid radioactive waste stream via process streams or leakages [IAEA SSG-40, 2016].

Although the composition of liquid radioactive waste may differ depending on the type of NPP, contributions to the liquid waste stream may derive from the following: (a) Reactor coolant letdown; (b) Evaporator concentrates; (c) Runoff from equipment drains; (d) Runoff from floor drains; (e) Laundry waste; (f) Contaminated oil; (g) Waste arising from the decontamination and maintenance of facilities and equipment.

Solid radioactive waste - It is generated in the operation, maintenance and decommissioning of a nuclear power plant and its associated processing systems for gaseous and liquid radioactive waste. The nature of such waste varies considerably from plant to plant, as do the associated levels of activity. Solid radioactive waste may consist of the following: (a) Spent ion exchange resins (both bead resins and powder resin); (b) Cartridge filters and pre-coat filter cake; (c) Particulate filters from ventilation systems; (d) Charcoal beds; (e) Tools; (f) Contaminated metal scrap; (g) Core components; (h) Debris from fuel assemblies or in-reactor components; (i) Contaminated rags, clothing, paper and plastic [IAEA SSG-40, 2016].

Decommissioning Waste - During decommissioning of the nuclear installation, administrative and technical actions are taken to allow the removal of some or all of the regulatory requirements from the facility. The activities involved in decontamination and dismantling of a nuclear facility and the cleanup of the site will lead to the generation of radioactive waste that may vary greatly in type, level of activity concentration, size and volume, and may be activated or contaminated. This waste may consist of solid materials such as process equipment, construction materials, tools and soils. The largest volumes of waste from the dismantling of nuclear installations will mainly be VLLW and LLW. To reduce the amount of radioactive waste, decontamination of materials is widely applied. Liquid and gaseous waste streams may also originate from decontamination processes.

Spent Nuclear Fuel – Spent fuel is generated from the operation of nuclear reactors of all types, including research, isotope production, power production, district heating and propulsion reactors. SF contains large quantity of energy, even after years of cooling in an SFP. It can be reprocessed, generating HLW after it, or if the country decides not to reprocess it, it can also be declared as HLW. By volume, HLW is less than 1% of the global volume of radioactive waste, but it consists of about 95% of the total activity of the radioactive waste [IAEA NW-T-1.14, 2022].

2.2.2. Spent Fuel Management

Spent nuclear fuel generated from the operation of nuclear reactors need to be safely and securely managed [IAEA SSG-15, 2020]. After approximately four years in a reactor, too little uranium-235 remains in the fuel to generate electricity. The spent fuel can be handled in one of two ways: Direct disposal, with the goal of eventually storing it in a stable geologic formation over the long term; Reprocessing SF, in a facility that recovers the useful components of the spent fuel (uranium and certain forms of plutonium) and returns them to the fuel cycle, where they are combined with newly mined uranium to produce more reactor fuel (see Figure 5 from Congressional Budget Office of United States) [CBO, 2007] . Any waste remaining from the spent nuclear fuel after the uranium and plutonium are removed is intended to be stored in a long-term repository. Thus, under either option, some form of long-term storage facility is necessary [CBO, 2007].

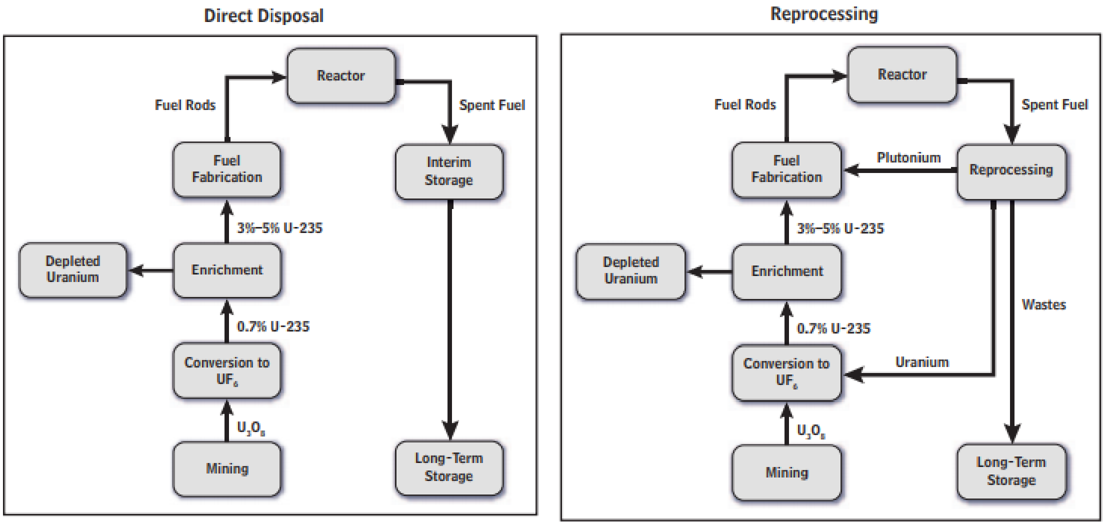


Figure 5 – Fuel Cycle with and without reprocessing.

France decided to develop nuclear energy after the first oil crisis in 1973, and after starting operation of its first PWR in 1977, they had by end of 1999, 58 PWRs progressively connected to the grid, with the proportion of electricity coming from nuclear reactors up to roughly 80%. In parallel, through its two major industrial operators, EDF and AREVA, France has developed and mastered a complete fuel cycle which is completely located in France except for the ore-mining activities. Figure 6 [POINSSOT et al, 2014] synthesizes the main steps of the French fuel cycle with the reference annual fluxes, calculated by 2010.

The recycling of SF is a major element of the strategy of the French nuclear sector, to manage the nearly 1150 tons of SF produced every year, France has decided for a closed nuclear fuel cycle by reprocessing SF. In doing so, the French nuclear industry can recover uranium and plutonium from the used fuel for reuse, thereby also reducing the volume of high-level waste and increasing its efficiency. The reprocessing process involves converting spent plutonium, formed in SF as a by-product of burning uranium, and new uranium into a “mixed oxide fuel” (MOX) that can be reused in NPPs to produce more electricity, as shown in figure 6. Through recycling, up to 96% of the reusable material in spent fuel can be recovered [IAEA, 2019].

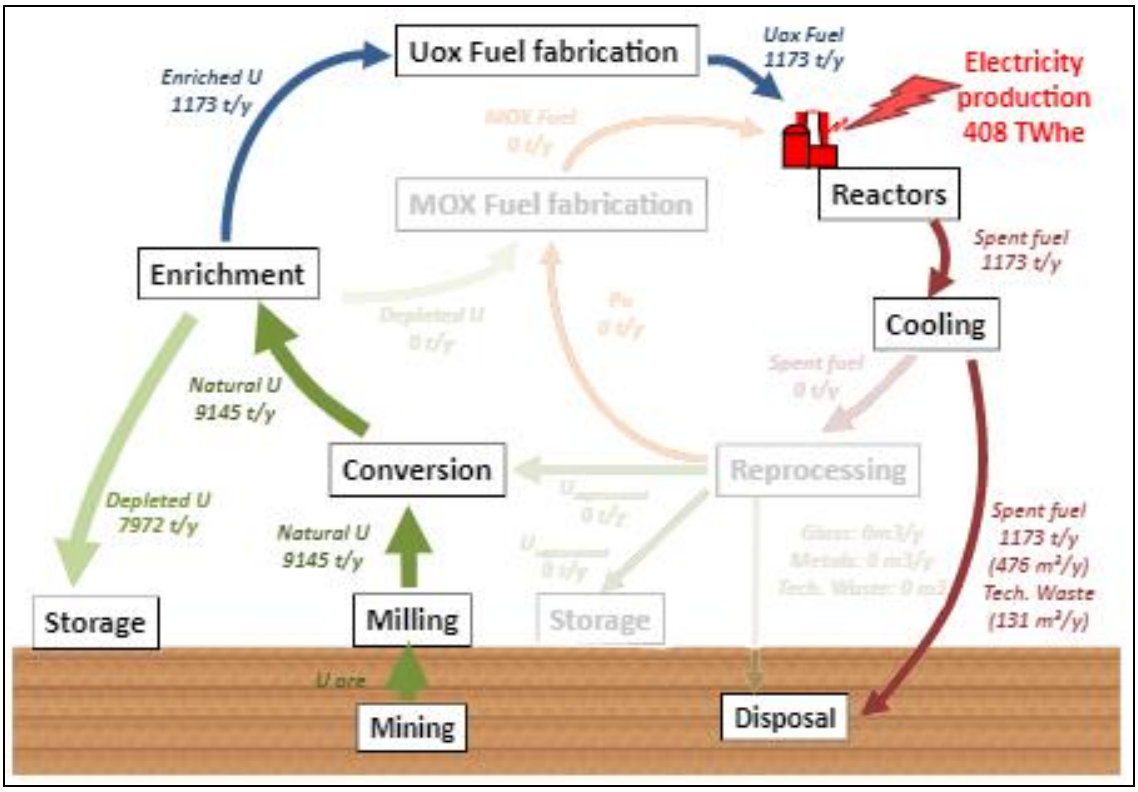


Figure 6 – French reference fuel cycle and its representative streams.

SF is initially stored at the nuclear plants in water-filled pools. Most of these pools were not designed for long term storage and many facilities have run out of capacity to store all the SF in their pools. At these facilities, dry storage systems or wet storage systems are utilized to store the SF. As more facilities run out of pool storage and as reactors continue to generate SF, the amount of dry storage is increasing [DOE, 2020].

HLW is the highly radioactive material resulting from the reprocessing of SF including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and other highly radioactive material that is determined, consistent with existing law, to require permanent isolation [DOE, 2020; WNA 2, 2021].

Aqueous reprocessing waste historically has been stored in underground metal storage tanks. Long term storage of reprocessing waste requires stabilization of the wastes into a form that will not react, nor degrade, for an extended period. Two treatment methods used for stabilization of the waste are vitrification or calcination. Vitrification is the transition of the reprocessing waste into a glass by mixing with a combination of silica sand and other constituents or glass forming chemicals that are melted together and poured into stainless steel canisters. Calcination of reprocessing waste is accomplished by injecting the waste with calcining additives into a fluidized bed to evaporate the water and decompose the remaining constituents into a granular solid material [DOE, 2012; DOE, 2020].

Spent nuclear fuel can also be considered as HLW if the country decides not to keep it for future use or reprocessing, and SF still contains significant amounts of fissile materials, other actinides, and fission products. It generates significant heat when freshly removed from the reactor, and is usually placed in storage pools, generally located within the reactor building. Eventually the spent fuel will be removed and subjected to a management option chosen from among a few possibilities as described in the following sections.

2.2.2.1 Spent Fuel Reprocessing

Reprocessing is a process or operation, the purpose of which is to extract radioactive isotopes from spent fuel for further use [IAEA GLOSSARY, 2018].

More than 90% of its potential energy remains in the fuel, even after five years of operation in a reactor. Used nuclear fuel can be recycled to make new fuel and byproducts [OFFICE OFNUCLEAR ENERGY, 2022].

In reprocessing process, the SF is dissolved and treated to separate the remaining fissile components from the fission products and activation products. Reprocessing operations generate solid, liquid, and gaseous radioactive waste streams. Solid waste such as fuel element cladding hulls, hardware and other insoluble residues is generated during fuel dissolution. This waste may contain activation products, as well as some undissolved fission products, uranium, and plutonium. The main liquid waste stream is the nitric acid solution, which contains both high levels of activity concentration of fission products and actinides in high concentrations. The principal gaseous waste stream is the off-gas, which contains rare gases and volatile fission products that are released from the spent fuel during the dissolution process. After solidification, HLW arising from reprocessing of spent fuel requires disposal in geological disposal facilities providing sufficient isolation and containment over long time periods [IAEA GSG-1, 2009].

In the 1950s, nuclear fission technology transitioned into a new source of electricity and commercial nuclear power plants were planned, built, and operated. In its earliest conception, civilian nuclear power was introduced with reprocessing of material as part of the plan. Used fuels from thermal reactors were to be reprocessed and the products, uranium, and plutonium, recycled into new fuel. Furthermore, it was understood early on that recycling of the material would require a fleet of fast reactors to effectively utilize the uranium available from mining operations, which is breeding and burning of plutonium [TAYLOR J.R.et al, 2015].

Several European countries, Russia, China, and Japan have policies to reprocess SF, although Government policies in many other countries have not yet come round to seeing used fuel as a resource rather than a waste [WNA 2, 2021].

Over the last 50 years or so the principal reason for reprocessing used fuel has been to recover unused plutonium, along with less immediately useful unused uranium, in the used fuel elements and thereby close the fuel cycle, gaining some 25-30% more energy from the original uranium in the process. This contributes to national energy security. A secondary reason is to reduce the volume of material to be disposed of as high-level waste to about one-fifth. In addition, the level of radioactivity in the waste from reprocessing is much smaller and after about 100 years falls much more rapidly than in used fuel itself [WNA, 2021].

Reprocessing SF to recover uranium as reprocessed uranium (RepU) and plutonium (Pu) avoids the wastage of a valuable resource. Most of it – about 96% – is uranium, of which less than 1% is the fissile U-235 (often 0.4-0.8%); and up to 1% is plutonium. Both can be recycled as fresh fuel, saving up to 30% of the natural uranium otherwise required. The RepU is chiefly valuable for its fertile potential, being transformed into plutonium-239 which may be burned in the reactor where it is formed [WNA 2, 2021].

So far, about 400,000 tons of used fuel has been discharged from commercial power reactors, of which about 30% has been reprocessed. Current commercial reprocessing capacity is about 2000 tons per year, as shown in table 1 [MAHER, C. J., 2015 and WNA 2, 2022].

Table 1 - Civil reprocessing plants currently operational

COUNTRY	SITE, NAME	COMMISSIONING DATE	THROUGHPUT (tHM YEAR $^{-1}$)	FUEL TYPE
UK	SELLAFIELD, MAGNOX	1964	1500	MAGNOX
	SELLAFIELD, THORP	1994	1000	LWR + AGR
FRANCE	LA HAGUE, UP2-800	1990	800	LWR
	LA HAGUE, UP3	1990	800	LWR
RUSSIAN	MAYAK, BB, RT-1	1976	400	LWR
JAPAN *	ROKKASHO	2022	800	LWR
INDIA	TARAPUR	1982	100	PHWR
	KALPAKKAM	1998	100	PHWR + FBR
	TARAPUR	2011	100	PHWR

SF from PHWRs such as CANDU is not attractive for reprocessing as it has a very low proportion of U-235 and Pu – typically 0.2% and 0.4% respectively. Also, for fast reactors, depleted uranium is plentiful and cheap [WNA, 2020].

2.2.2.2 Disposal of Spent Fuel and High-Level Waste

Disposal is the emplacement of waste in an appropriate facility without the intention of retrieval. The use of the term 'disposal' indicates that there is no intention to retrieve the waste. If retrieval of the waste at any time in the future is intended, the term 'storage' is used [IAEA Glossary, 2018].

The last step of the long-term management of radioactive waste is disposal. Disposal in near surface repositories is the generally accepted solution for Very Low-Level Waste (VLLW) and Low-Level Waste (LLW). Intermediate Level Waste (ILW) and High-Level Waste (HLW), as well as spent fuel declared as waste, require disposal in an underground repository [IAEA NW-T-1.25, 2020].

For used fuel designated as HLW, the first step is storage to allow decay of radioactivity and heat, making handling much safer. Storage of used fuel may be in ponds or dry casks, either at reactor sites or centrally. Beyond storage, many options have been investigated which seek to provide publicly acceptable, safe, and environmentally sound solutions to the final management of radioactive waste. The most widely favored solution is deep geological disposal (GD). The focus is on how and where to construct such facilities [WNA 3, 2021].

The term ‘geological disposal’ refers to the disposal of solid radioactive waste in a disposal facility located underground in a stable geological formation to provide long term containment of the waste and isolation of the waste from the accessible biosphere. Disposal means that there is no intention to retrieve the waste, although such a possibility is not ruled out. GD is a method for disposing of the more hazardous types of radioactive waste, which pose a significant radiological hazard over long time periods [IAEA SSG-14, 2011].

HLWs need to be isolated from the biosphere for tens to hundreds of thousands of years. The relevant timescale and specific need for containment and isolation depend on the specific waste properties and must be demonstrated for as long as the waste presents a potential hazard. It is not possible to ensure this level of isolation in facilities at the surface or at depths in the order of tens of meters to a few hundred meters. These types of waste require disposal at a depth of several hundred meters in a stable geological environment that can provide isolation and containment for the needed timescale. This disposal option is referred to as geological disposal [IAEA SSR-5, 2011].

The natural and engineered barriers need to isolate the waste and retard, delay and attenuate the migration of radionuclides so that radionuclide releases into the biosphere do not pose a hazard to people and the environment. This places high requirements on the geological environment in which a geological disposal facility is located. It needs to be a geologically stable environment with low seismic activity or active faults, where water movement is slow and in which the groundwater chemistry is favorable for ensuring adequate safety performance of the disposal system [IAEA NW-T-1.25, 2020].

There are three countries with the most advanced GD programs. Finland started excavation of its 400-450m deep repository in hard rock for spent nuclear fuel in 2021 and disposal operations are planned to commence in the 2025. Figure 7 [WNN, 2021] shows an illustrative picture of its Onkalo repository. Sweden has selected a hard rock site for its 500m deep repository and has received license for construction in January 2023, and it is planned to put in operation in 10 years. Figure 8 shows SKB’s Swedish deep GD concept [Prospect Law, 2021]. France is also planning to have its own DGR and expects to have a construction license until 2024 and expects to reach approval by all authorities including the French Nuclear Safety Authority in 4 to 5 years. Construction process is anticipated to take 10 to 15 years. Several other countries are at various stages of facility site selection with the UK having recently embarked on a new siting process [PROSPECT LAW, 2021; WNN, 2021; NEA/OECD, 2020; SKB, 2023].

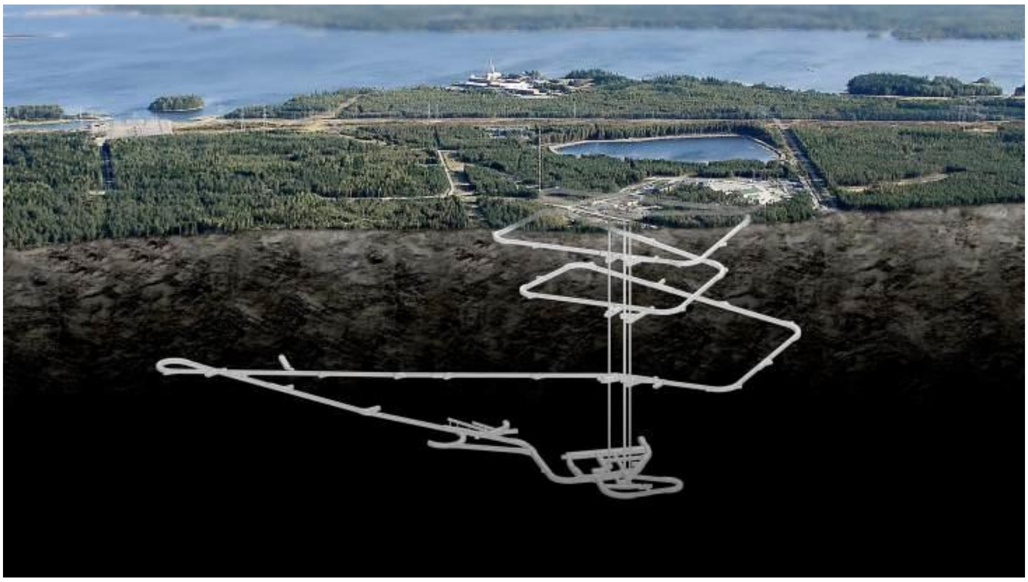


Figure 7 – Finland´s planned Onkalo repository - illustrative picture

Figure 8 – Figure - SKB’s Swedish deep geological disposal concept

2.2.2.3 Spent Fuel Storage

Despite of choosing as management option to direct disposal or reprocessing, either management option will involve several steps, which will necessarily include storage of the spent fuel for some period of time. This time for storage can differ, depending on the management strategy adopted, from a few months to several decades.

The time for storage will be a significant factor in determining the storage arrangements adopted. The final management option might not have been determined at the time of design of the storage facility, leading to some uncertainty in the storage period that will be necessary, a factor that needs to be considered in the adoption of a storage option and the design of the facility. Storage options include wet storage in some form of storage pool, or dry storage in a facility or in storage casks built for this purpose. Storage casks can be in a designated area on a site or in a designated storage building [IAEA SSG-15, 2020].

There are two acceptable storage methods for spent fuel after it is removed from the reactor core [U.S.NRC, 2021]:

- Spent Fuel Pools - Currently, most spent nuclear fuel is safely stored in specially designed pools at individual reactor sites around the country (See Figure 9 [Eletronuclear, 2021]).

Figure 9 – Spent Fuel Pool of Angra 2 on the left and Angra 1 on the right

- Dry Cask Storage – SF is stored in dry cask storage systems at independent spent fuel storage facilities (ISFSIs) at the following sites:
    - ✓ At Reactor – It may use dry storage systems when approaching their pool capacity limit. Figure 10 [PETRONOTICIAS, 2021] shows the ISFSI Dry Storage for 72 casks, located at Angra dos Reis, in CNAAA site, Brazil.

Figure 10 – Photos of the CNAAA ISFSI - Dry Storage

- ✓ Away-From-Reactor – It may use dry storage systems at one of the following locations:

  - Decommissioned Reactor Sites – After terminating reactor operations and removing structures used in reactor operations, the licensee stores spent fuel on-site pending off-site transport to either a site-specific ISFSI that is authorized to receive the spent fuel, or a permanent geologic repository licensed for disposal.

  - Consolidated Interim Storage Facility (CISF) – Dry cask storage at an away-from-reactor site pending disposal at a permanent disposal facility. Figure 11 [Holtec International, 2021] shows the Holtec´s design illustration of the HI-STORE, CISF designed for 10.000 SF casks, southeastern of New Mexico.

Figure 11 – HISTORE Interim illustrative picture from Holtec International

Challenges and opportunities of SFM options while using open NFC and/or closed NFC, and it the characteristics of each other must be considered when selecting the best strategy for the country. Regarding uranium consumption, closed NFC increases efficiency, and the consumption is reduced by a factor of more than 50%, but it requires more complexity and technology and a new type of reactor enable to use the reprocessed fuel. Also, the maturity of technology is a big advantage in the open NFC, as we have limited experience with the closed NFC. Closed NFC reduces the production of waste considerably by a factor 1/3 and its radiotoxicity. When it comes to security and safety, in the open NFC, as we have fewer handling steps and initially is easier, but in terms of long-term safety, the radiotoxicity is higher than the closed NFC. In the end, looking through safeguard's perspective, it is easier to control the open NFC, as we have less amount of sensitive material and smaller quantity of processes for verification. Table 2 shows the main characteristics related to open and closed NFC [SCHWENK-FERRERO, 2021; EASAC, 2014].

Table 2 - Main differences and challenges related to Open Nuclear Fuel Cycle and Closed Nuclear Fuel Cycle

ASPECT	OPEN NFC	FULLY CLOSED NFC
URANIUM CONSUMPTION	- 20 TONNES U/TWh (i.e., 100 TO 200 TONNES OF URANIUM PER YEAR OF REACTOR OPERATION)	+ CONSUMPTION REDUCE BY A FACTOR OF 50 TO 100
COMPLEXITY OF THE TECHNIQUES	+ FEW TECHNICALLY RELATIVELY SIMPLE MANAGEMENT AND HANDLING STEPS	- COMPLEXITY INCREASED BY USE OF REPROCESSING AND FAST NEUTRON REACTOR SYSTEM
MATURITY OF THE TECHNIQUES, DEVELOPMENTS REQUIRED	+ LONG EXPERIENCE WITH INTERIM STORAGE	- LIMITED EXPERIENCE WITH OPERATION OF LAST NEUTRON REACTORS, NEW REACTORS IN DESIGN PHASE
	- ENCAPSULATION AND DISPOSAL IN THE DESIGN AND LICENSING PHASE	- DEVELOPMENTS FOR THE SNF PARTITIONING AND TRANSMUTATION TECHNIQUES
WASTE DISPOSAL	- LARGE REPOSITORY FOOTPRINT (DUE TO WASTE VOLUME AND HEAT RELEASE)	+ REDUCTION FOR THE FOOTPRINT BY A FACTOR OF 1/3 (DUE TO REDUCED VOLUME AND HEAT RELEASE FOR HIGH LEVEL WASTE)
	- VERY LONG TIMESCALE TO REACH RADIOTOXICITY OF NATURAL URANIUM (200.000 YEARS)	+ IF PARTITIONING AND TRANSMUTATION IS APPLIED: SIGNIFICANT REDUCTION OF THE TIMESCALE TO REACH RADIOTOXICITY OF NATURAL URANIUM (THEORETICALLY LESS THAN
SAFETY	+ FEWER HANDLING STEPS	- MORE OPERATIONS AND TRANSPORT
	- MORE COMPLICADED LONG-TERM SAFETY	+ POTENTIAL FOR SIMPLE LONG-TERM SAFETY
SECURITY	+ FEWER HANDLING STEPS	- MORE OPERATIONS AND TRANSPORT
	+ NO SEPARED SENSITIVE (FISSILE) MATERIAL	- SENSITIVE MATERIAL SEPARATED
PROLIFERATION	+ NO FREE SENSITIVE MATERIAL - LONG-TERM SAFEGUARDS OF THE REPOSITORY	+ LESS OR NO ENRICHMENT NEEDS - SIGNIFICANT AMOUNT OF SENSITIVE MATERIAL SEPARED IN THE PROCESS + NO SENSITIVE MATERIAL IN REPOSITORY

2.2.2.4 Spent Fuel and HLW Management in the World

As a growing number of countries use nuclear technology to generate electricity and radioactive material for many other purposes, there is significant progress in the safe and effective management of radioactive waste and spent nuclear fuel arising from these activities, including the development of deep geological disposal for SF and HLW.

The scientific consensus today is that deep geological repositories (DGRs) are a safe and effective approach to permanently dispose of SNF/HLW. Independent national regulators, applying globally accepted radiation protection standards, have endorsed their effectiveness to isolate SF/HLW from humans and the environment [NEA/OECD, 2020].

The strategy for management SF depends on the fuel cycle option of each country. In the open cycle option, spent fuel is stored for several decades to allow the decay heat to be reduced. After a period of storage, the spent fuel will be encapsulated in a robust, corrosion resistant container to meet disposal acceptance criteria and will be disposed of in a geological disposal facility (GDF). In the closed cycle the spent fuel is reprocessed in order to recover valuable fissile materials (uranium and plutonium). In reprocessing spent fuel is separated into several main components: uranium, plutonium and HLW (containing minor actinides, fission and activation products). HLW (along with other waste such as LLW and ILW) resulting from reprocessing is then stored to allow the decay heat to be reduced pending future disposal, normally in a GDF [IAEA NW-T-1.14, 2022].

A summary of SF Management options worldwide can be shown in Appendix C. It shows that most countries have adopted or use for referencing the open cycle, while the countries with some of the largest nuclear programs, e.g., France, Russian Federation, Japan, India and China, have adopted the closed cycle. Some countries with a small nuclear fleet, like the Netherlands, have also opted for the closed cycle strategy, with reprocessing services provided by one or more of the larger countries with this capability. Appendix C shows that although several countries have chosen open or closed cycle, there are also countries that are keeping their options open [IAEA NW-T-1.14, 2022]. Beyond Brazil, Argentina, Belgium, Republic of Korea, Mexico and Ukraine, have not reached to a SF strategy (6 of the 29 countries listed in Appendix C).

2.3. Multi-criteria Decision Method Techniques

Multi-criteria decision analysis (MCDA) is a multi-step process consisting of a set of methods to structure and formalize decision-making processes in a transparent and consistent manner [ZLAUGOTNE et al., 2020]. Over the years, MCDA has developed many methods and software to resolve all kinds of complex problems in several areas as energy-environmental-sustainability, supply chain and material management, quality management, quality management, Geographic Information System (GIS), construction and project management, safety and risk management, manufacturing systems, technology management, operation research and soft computing, strategic management, knowledge management, production management, tourism management and other fields [MARDANI et al., 2015].

Multi-criteria decision making (MCDM) is one of the most well-known branches of decision making. According to many authors [TRIANTAPHYLLOU, 2000] MCDM is divided into multi-objective decision making (MODM) and multi-attribute decision making (MADM).To be able to use the MCDA method, it is important to define the problem, alternatives, and criteria that may be different types of costs, environmental impact indicators, social indicators, energy efficiency, quality and other specific criteria that are important to the related problem. When there are many alternatives for one problem, it is important to find the most suitable alternative with the best cost criteria, lowest impact on environment, and good energy efficiency. This can be achieved by using the MCDA method as a tool for comparing alternatives [IAEA, 2019., ZLAUGOTNE et al., 2020., TRIANTAPHYLLOU, 2000].

The problem of selecting the best strategy for Spent fuel Management has only one objective which is to select the best alternative for the country and so it is a MCDA problem. Therefore, this thesis will review the more relevant MCDA methods to select the method to be used.

2.3.1 International and Nuclear experience

In the following sections it will be described international experience, literature, and best practices of the application of MCDM techniques and application in nuclear area.

2.3.1.1 IAEA Experience in MCDA methods of Nuclear System Energy options

IAEA has published a guide for application of MCDA Methods to comparative evaluation of nuclear energy system options that provides a good path to start the evaluation of Spent Fuel Management [IAEA, 2019]. The document was a result of a project prepared by experts nominated by several IAEA member States representing technology holder countries with large nuclear energy programs and active research and development projects, technology users and newcomer countries that are considering or are in the process of starting a nuclear program.

According to IAEA [IAEA, 2019], the decision support process begins with the identification of the decision maker's problem to be solved and a group of subject matter experts and stakeholders (persons interested in a certain decision), and then iteratively goes through the following steps:

(I) Problem formulation and goal to be achieved;

(II) Formulation of possible alternatives to solve the problem;

(III) Identification of indicators;

(IV) Indicator evaluation;

(V) Selection of an MCDA method;

(VI) Construction of an objectives tree and weight assignments (including uncertainties);

(VII) Determination of alternative ranking based on the selected MCDA method;

(VIII) Sensitivity and uncertainty analysis;

(IX) Conclusion and recommendations.

The methodology has a theoretical basis and mathematical foundation for the comparative evaluation of options involving Nuclear Energy Systems (NES), considering the multiple areas from economics and non-proliferation aspects through to public opinion issues, the technical details of reactor performance and waste generation. Different groups of people with a stake in the results of the energy option analyses (stakeholders) judge the importance of these areas differently, leading to the need for the application of MCDA methods and deep understanding of their strengths and limitations. Furthermore, it provides a guidance development on key indicator (KI) sets for comparative evaluation of different NES options, adaptation, and elaboration of the state-of-the-art methods for expert judgement aggregation and uncertainty analysis methods to enable effective comparative evaluation of such options and performed case studies.

In IAEA study, it has been selected Key Factors (equivalent to criteria) to evaluate each case. IAEA have evaluated each scenario from the following general perspectives:

- **Safety** - In general, sustainability evaluations in safety are applicable to more mature designs, leading to innovative concepts with less operational experience to be less safe than more stablished technologies. Safety considerations are very important in the evaluation of a strategy.

- **Economics -** Economic indicators include the cost to establish, operate and decommission energy systems. In some evaluations, this is extended to include dimensions such as life cycle costs, financing considerations and jobs creation. Nuclear systems are generally much more capital intensive than other options. Also important is the experience of the operator with design, technology and licensing aspects of the chosen path.

- **Waste Management** - It has to be considered to keep the generation of radioactive waste (measured, for instance, in tons or in volume units) by an NES and its impact to the minimum practicable level.

- **Environmental** – Includes resource utilization (also sustainability of materials use), land and water use, waste management, carbon emission, and radiological and chemical impacts. Waste management is a major area when comparing different advanced NES fuel cycles, but it is of less importance when comparing current proven NESs. Advanced NESs with recycling of SF significantly modifies the amount of waste generated and the characteristics and hazards associated with those wastes.

- **Proliferation Resistance and physical protection** – Typical areas of security, proliferation resistance and physical protection, along with societal opinion/support for different energy generation technologies. It is required to have high considerations regarding safeguards to keep nuclear material safe and secured.

- **Maturity of Technology** – The technology provided in the NES or strategy needs to be “proven” and “mature” before it is included in the design for execution. For higher level of maturity, it needs to have already been applied in a prototype (a system, subsystem, or component), tested in a relevant or operational environment. Less mature technologies are characterized by greater uncertainty owing to insufficient detail in areas such as design information.

- **Other Aspects –** Specific aspects related to the country, such as politics, infrastructure, capability, etc.

2.3.2.2 Decision Framework for Evaluating Advanced Nuclear Fuel Cycles - EPRI Guide

EPRI [EPRI, 2011] has realized that decision and supporting analysis tools and criteria are needed to ensure that an appropriate mix of technologies is identified and pursued to demonstration. Due to the range of technical and non-technical factors that feed into the decision-making process, selection and weighting of decision criteria require extensive review. This transparency and traceability call for a framework for structuring information, criteria, weighting of those criteria, and identifying knowledge gaps, especially to provide sufficient documentation of decision-making processes, which will certainly evolve over the long timeframes required for implementing a fruitful a long-term fuel cycle research, development, and demonstration.

EPRI framework has the purpose of Explore different fuel cycle options to gain better understanding of how and when a change to assumptions, conditions, factors, and weighting of those factors might drive different fuel cycle decisions.

The Decision tool process is divided in: Organization of the Decision Process; Definition of the Decision Metrics; Flowchart Element Assessments; Evidence Database and Flowchart Option Path Assessment.

2.3.2.2.1 Organization of Decision Process

In a starting generic level, it is proposed to build a flowchart that depicts a sequence which the key issues or elements are addressed, with recommended three fundamental levels of assessment comprising the overall decision framework as follows.

2.3.2.2.2 Alignment of proposed fuel cycle options with strategic objective

The following 5 items need to be evaluated from the strategic perspective:

I. **Sustainability of fuel Supply** - Need to be adequate, reliable fuel supply to support the current, projected, and/or desired nuclear power generation for the relevant timeframe;

II. **Proliferation Resistance and Security** – Challenges and concerns that arise with the decision and choice to be made, that affects the availability and spread of special nuclear materials and associated technologies**;**

III. **Waste Management** – Universal need to appropriately manage SF and RW**;**

IV. **Fuel Cycle Safety –** Addresses the desire to prevent unacceptable releases of Radioactive Material to environment and unacceptable levels of exposure of public and workers;

V. **Economic Competitiveness** – Encompasses factors that drive the relative cost / benefit evaluation.

2.3.2.2.3 Feasibility of possible implementation pathways

It is important to analyze the scenarios in a “how”, “what and why” perspective to achieve the defined strategy or objectives, considering limitations imposed by external restrictions, resources, requirements fulfillment, etc.

2.3.2.2.4 Readiness of technology for deployment

Technical readiness review evaluates the status of technologies for deployment of the strategy chosen and desired goal. This technology evaluation is at the heart of the framework. It must be evaluated if more research or development need to be executed to support the decision, also considering licensing and regulatory framework.

2.3.2.2.5 Decision Metrics

The proposed Figure of Merit (FOM) for evaluating the individual elements of a flowchart is expressed by the term “favorability”. Factors that could be included are:

- Conformity to primary strategic issues as: sustainability, proliferation and physical security, waste management, fuel cycle safety and economic competitiveness.
- Licensing and regulations requirements.
- Technical maturity of technology.
- Any important issue related to the project critical path and availability of resources.

A generic guideline for quantifying the favorability figure of merit is shown in Tables 3 and a generic guideline for quantifying uncertainty of the FOM in Table 4.

Table 3 – Generic guidelines for quantifying the favorability Figure of Merit

	Suggested Guideline	**Discussion**
1	ABSOLUTELY POSITIVE	There should be no uncertainty or potential for unforeseen problems to arise. This should be supported by overwhelming evidence from extensive experience
0,9	GENERALLY INCREASING FAVORABILITY	Higher ratings suggest a greater willingness to commitment resources for implementing the strategy. This should be supported by a greater body of evidence
0,8		
0,7		
0,6		
0,5	NEUTRAL ATTITUDE	Evidence indicates that there may be problems, but they are generally not severe and are surmountable
0,4	GENERALLY DECREASING FAVORABILITY	Lower rating can reflect both know problems and/or a lack of knowledge. Both of these should be flagged in follow-up actions
0,3		
0,2		
0,1		
0	UNACCEPTABLE	If this rating appears on one strategic issue, it should be an overall showstopper. A rating such as this would indicate that extensive follow-up actions are needed, or the course of action should be abandoned

In addition, it is recommended to do a second component of the assessment by assignment of some measure of confidence and uncertainty in the favorability FOM selected. Table 4 [EPRI, 2011] provides a proposal of guidance for this judgment.

Table 4–Generic guidelines for quantifying uncertainty figure of Merit

RATING	**IMPACT ON FOM ESTIMATE**	**EXAMPLES OF THOUGHT PROCESS THAT COULD RESULT THE UNCERTAINTY FOM**
0	ABSOLUTELY CERTAIN OF **FOM** ESTIMATE	RESERVED FOR ESTALISHED FACTS WITH EXTENSIVE EVIDENCE TO SUPPORT THEM
1	MINOR	MATURE TECHNOLOGY AND EXTENSIVE EXPERIENCE SUPPORT THIS ESTIMATE, WITH EXCELLENT DOCUMENTATION. IF THERE IS UNCERTAINTY, CONTROL CAN BE EXERCISE TO MAKE THE ACHIEVE THE ESTIMATE
2	MODERATE	EVIDENCE SUPPORTING THE ASSESSMENT PROCESS IS NOT COMPREHENSIVE, AND THE ASSESSMENT COULD BE CHANGED AS NEW EVIDENCE IS IDENTIFIED
3	SIGINIFICANT	ENOUGH GAPS AND HOLES IN EVIDENCE TO REQUIRE ADDITIONAL RESEARCH AND ALLOCATION OF RESEARCH TO GAIN MORE CONFIDENCE IN ESTIMATE OR COURSE OF ACTION
4	LARGE	THERE IS A LACK OF OR CONTRADICTORY EVIDENCE SUPPORTING AN ASSESSMENT. THE FOLLOW-UP ACTIONS SHOULD IDENTIFY NEEDS FOR ADDRESSING THIS PROBLEM
5	EXTREME	AT THIS POINT THE **FOM** IS JUST A PLACE KEEPING GUESS. THE FOLLOU-UP ACTIONS MAY NOT EVEN BE ABLE TO PROVIDE A REASONABLE PATH FORWARD TO RESOLVE ISSUES AT THIS TIME

Both FOMs combined could be used to show the overall status of options being investigated.

2.3.2.2.5 Flowchart Elements Assessments

After creating a flowchart of the process and possible paths, it is evaluated each element in the flowchart. Once the evaluation of a path to the objective is completed, the user can review the assessments of all the flowchart's elements for consistency and combine the assessments using appropriate logic to express an overall FOM for that path.

The framework consists of flowcharts and forms that assist the user's thought process to make decisions at a level commensurate with the phase of the program being evaluated. It enables diverse stakeholders to evaluate strategies, from different perspectives and priorities and their evaluation of similar strategies could result in differing conclusions based on key issues as well as the bases for the evaluation of key scenario elements.

2.3.2 Overview of the main MCDA methods

MCDA methods has grown as a part of operations research, concerned with designing computational and mathematical tools for supporting the subjective evaluation of performance criteria by decision-makers [MARDANI et al., 2015]. There are many methods that can be used for solving problems and they can be arranged according to different parameters. Each MCDA method has its own calculation method by which alternatives are queued and it is not possible to claim that using specific methods with the same input data will lead to the same result [ZLAUGOTNE et al., 2020; IAEA, 2019; TRIANTAPHYLLOU, 2000; MARDANI et al; 2015].

A large number of MCDA methods has been developed. Some of the most relevant are the followings [ZLAUGOTNE et al., 2020; IAEA, 2019; TRIANTAPHYLLOU, 2000; MARDANI et al., 2015]:

- AHP - Analytic Hierarchy Process Method [SAATY and VARGAS 2001];
- TOPSIS - Technique for Order Preference by Similarity to Ideal Solution [SAŁABUN et al., 2020];
- VIKOR – Vise Kriterijumska Optimizacija I Kompromis no Resenje [SAŁABUN et al., 2020];
- MULTIDORA - Multi-Objective Optimization on the basis of a Ratio Analysis plus the full MULTIplicative form [HAFEZALKOTOB et al., 2018];

- PROMETHEE-GAIA - Preference ranking organization method for enrichment evaluations [BRANS and MARESCHAL, 2005];
- COPRAS - Complex Proportional Assessment [SAŁABUN et al.., 2020]
- WSM - Weighted Sum Model [WINDARTO and MUHAMMAD, 2017].
- Elementary Judgement aggregation and multi-attribute value theory (MAVT) and Multi-attribute utility theory (MAUT) [JIMÉNEZ-MARTÍN et al., 2014]
- ELECTRE - *Élimination et choix traduisant la réalité* — elimination and choice expressing reality [FIGUEIRA et al, 2010]

It can be difficult to select one specific method as in most of the cases, there is more than one recommended [TRIANTAPHYLLOU, 2000]. Triantaphyllou concluded in its methods comparative study that to solve a certain problem, one may never know which is the best decision method, even if the perfect knowledge in the input of structure of the MCDM is assumed and that may never be a single alternative for one solution. Likewise, [ZIMMERMAN and GUTSHE, 1991] also say that finding the "best" MCDM method is a very elusive goal and very difficult decision.

2.3.3 MCDA method selection

Several comparisons of different MCDA methods could have been performed in the literature with the objective to choose the more recommended method to each problem, and what it is a common understanding is that there is no single method to be used, but some recommended methods for each case [ZLAUGOTNE et al., 2020; IAEA, 2019; TRIANTAPHYLLOU, 2000; MARDANI et al; 2015].

IAEA has performed a recent comparative study of MCDA methods to evaluate Nuclear Energy System (NES) options for a specific case as shown in [IAEA, 2019]. The study counted with the participation of several nuclear specialists throughout the world. It has been compared "Elementary judgement aggregation", MAVT, MAUT, TOPSIS, ELECTRE, PROMETHEE and AHP methods, which were the more relevant methods in the specialist's perspective for evaluation of the NES scenarios that were studied. The study reveals and conclude that the five methods provide similar ranking results, and besides the simple score model, all of them had the same scenario chosen as best to be selected, and all of them besides the 11 selected, had the same result for the 4 best strategies in the document [IAEA, 2019].

Using the same IAEA method [IAEA, 2019] method, to find the best indicated deployment scenario in Russia [ANDRIANOV et al, 2019], with same methods of MDCA

(Simple scoring Model, MAVT / MAUT, AHP, TOPSIS, PROMETHEE) for evaluation, they have reached to the same conclusion. They determined that the use of different methods of MDCA to compare the nuclear energy deployment scenarios, despite some differences in the rankings, leads to well-coordinated and similar results. [SCHWENK-FERRERO and ANDRIANOV, 2019] have used the same methodology for evaluating nuclear waste management strategies and have found the same results for the 6 methods.

In APPENDIX A, it is shown the application, advantages, and disadvantages of the more relevant CDM methods [KUMAR et al., 2016].

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2.3.3.1 The AHP method

Kumar has described AHP as simple, flexible, and intuitive method that has the ability to handle criteria qualitative and quantitatively. However, it becomes more complex when it is applied over many criteria, as may lead to inaccurate judgements and due to the increase of comparisons needed when more than seven criteria are selected [KUMAR et al., 2016, RAMANATHAN and GANESH, 1995; MILLET and HARKER, 1990; ZLAUGOTNE et al., 2020]. Additionally, the study shows that AHP has been used several times to solve energy industry decision problems and affirms that AHP, due to its simplicity in procedure, has gained popularity although few outranking techniques like ELECTRE III and PROMETHE are also popular. But no single MCDM model can be ranked as best or worst. Every method has its own strength and weakness depending upon its application in all the consequence and objectives of planning.

[ZLAUGOTNE et al., 2020] has also compared TOPSIS, VIKOPR, COPRAS, MULTIMOORA, PROMETHEE-GAIA and AHP methods as shown in APPENDIX B. In the AHP method an important indicator is the number of criteria, and it affects result consistency because more than seven criteria lead to an increase in inconsistency. The AHP model facilitates the organization of the various variables in levels of hierarchy, and it helps experts to evaluate criterion against criterion [ZLAUGOTNE et al., 2020].

ABBAS MARDANI [MARDANI et al, 2015] has performed a wide literature review and research about the MCDM techniques where he pointed out 393 published articles extracted from “Web of Science” in more than 120 journals, from 2000 until 2014. In this review, AHP was recognized as far more used than other methods with 32,57% (128 articles) followed by “Hybrid MCDM” (method based on previously developed well-known methods, such as AHP and TOPSIS) with 16,28% (64 articles). The hybrid method has

AHP combined with other technique in 30 articles (47% of total hybrid methods). The Summary of this research about the application of each method is shown in table 3 [MARDANI et al, 2015]. In a similar review, MORKŪNAITĖ has selected 52 articles, where AHP has been used in 38% of the studies and it was far the most used method [MORKŪNAITĖ et al, 2019].

Table 5 – Summary of MCDM applications methods resulted of literature review by Abbas Mardani from 2000 until 2014

DECISION MAKING TECHNICHES	FREQUENCY OF APPLICATION	PERCENTAGE
AHP	128	32,57
Hybrid MCDM	64	16,29
ELECTRE	34	8,65
DEMATEL	7	1,78
PROMETHEE	26	6,62
TOPSIS	45	11,45
ANP	29	7,38
Aggregation DM methods	46	11,70
VIKOR	14	3,56
Total	**393**	**100**

Besides the wide use of AHP method in many different areas, it also been extensively used in nuclear industry in the last years as shown below.

- SF, RW management strategy evaluation [DYASI; 2021; IAEA, 2019, ANDRIANOV et al, 2019; SCHWENK-FERRERO and ANDRIANOV, 2019; NOH, 2016; TAJI et al, 2005; SAATY, 1982].
- Decommissioning and Disposal of RW and disposal site selection [MAIA, 2022; DYASI, 2020; MADEIRA et al, 2016, RABOSHAGA et al, 2016; MARTINS, 2009].
- Nuclear energy systems strategy [KIM et al, 2021; POINSSOT et al, 2014, IAEA 2019; YOON, 2016].

Considering the past experiences described, besides the specific characteristics of each MCDA method, it is recognized that after comparative studies, the ultimately most used and relevant methods have similar results when evaluating a decision problem [IAEA, 2019; ANDRIANOV et al, 2019; SCHWENK-FERRERO and ANDRIANOV, 2019].

AHP is the most popular, easy to use, flexible, intuitive and is a very well-known method used in all kinds of complex and strategic problems [MAIA, 2022; KUMAR et al, 2016; MARDANI et al, 2015; BHUSHAN N. AND RAI, 2004; SAATY et al, 2001; IAEA

2019; ZLAUGOTNE et al., 2020; GRECO et al, 2016]. Additionally, the AHP method has also been very used in the nuclear industry, Spent Fuel and waste management and nuclear fuel cycle strategy in the last years [IAEA, 2019; MAIA, 2022; DYASI, 2020; MADEIRA et al, 2016, RABOSHAGA et al, 2016; NOH, 2016; MARTINS, 2009].

Complex decision problems involving conflicting objectives and criteria such as Spent Fuel and Radioactive Waste Management associated with uncertainties and the decision maker must decide between a multiplicity of factors and conflicting objectives of technological, environmental, financial, social, and political nature [SAATY and GHOLAMNEZHAD, 1982]. Such complex problem is a typical MCDM problem and can be adequately solved using AHP.

Due to all the previous mentioned AHP advantages of being easy to apply, very experimented and accepted, providing a consistency check in its structure, being versatile, for this thesis it was selected the AHP MDCA method as a basis for its methodology for reaching to the best decision related to Spent Fuel Management Strategy in Brazil.

3. Theoretical Foundation

3.1 Analytic Hierarchy Process (AHP) Method

The analytic hierarchy process (AHP), developed by Saaty [Saaty, 1977], has been an effective tool in structuring and modeling multi-objective problems for decades in all kinds of complex decision makings problems for planning, prediction, prioritization, resource allocation, strategy evaluation, economics and many complex decisions in the industry [TOLOI, 2022; MARDANI et al., 2014; OSURI, 2014; KIM et al., 2021; POINSSOT et al, 2014, IAEA 2019, YOON, 2015; MAIA, 2022; DYASI P.B, 2020; MADEIRA et al, 2016, RABOSHAGA et al, 2016; SAATY and GHOLAMNEZHAD, 1982].

The simplest form used to structure a decision problem is a hierarchy consisting of three levels: the goal of the decision at the top level, followed by a second level consisting of the criteria by which the alternatives, located in the third level, will be evaluated. Hierarchical decomposition of complex systems appears to be a basic device used by the human mind to cope with diversity. One organizes the factors affecting the decision in gradual steps from the general, in the upper levels of the hierarchy, to the particular, in the lower levels. The purpose of the structure is to make it possible to judge the importance of the elements in a given level with respect to some or all of the elements in the adjacent level above [SAADY and VARGAS, 2001].

The Analytic Hierarchy Process (AHP) provides the objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in reach to a decision. AHP is a method of breaking down a complex, unstructured situation into its component parts; arranging these parts, or variables, into a hierarchic order; assigning numerical values to subjective judgments on the relative importance of each variable; and synthesizing the judgments to determine the overall priorities of the variables.

The AHP works by developing priorities for alternatives and the criteria used to judge the alternatives. Criteria are selected by a decision maker. First, priorities are derived for the criteria in terms of their importance to achieve the goal, then priorities are derived for the performance of the alternatives on each criterion. These priorities are derived based on pairwise assessments using judgment or ratios of measurements from a scale if one exists. With the AHP a multidimensional scaling problem is thus transformed to a unidimensional scaling problem [SAATY and GHOLAMNEZHAD, 1982; SAATY, 2001; TRIANTAPHYLLOU, 2000; BILAL et al, 1999].

The results of pairwise comparison are assembled in reciprocal matrices (organized with the expert’s evaluation) which are used to derive the relative weights of importance. After that, it is converted to an eigenvector. The principal eigenvector represents the priorities (relative weights) and the maximum eigenvalue allows evaluating the inconsistency of the judgment matrices (SAATY, 1977). The eigenvector shows the dominance of each element with respect to the other.

The most rigorous, but also the most computationally demanding approach consists in calculating the normalized principal eigenvector of the matrix (SAATY, 2001). Instead, a much easier way to determine criteria weights consist in the calculation of the geometric mean of each row and the successive normalization of the resulting new column of the pairwise comparison matrix [DEAN, 2022].

Today decision making has become a science. The AHP contributes to solving complex problems by structuring a hierarchy of criteria, stakeholders, and outcomes and eliciting judgements to develop priorities. It also leads to prediction of likely outcomes according to these judgements. The outcomes can be used to rank alternatives, allocate resources, conduct benefit/cost comparisons, exercise control in the system by evaluating the sensitivity of the outcome to changes in judgement, and carry out planning of projected and desired futures. [SAATY, 2012]

As a decision support a MCDM framework is recommended to be applied when many conflicting criteria and a large number of stakeholders are going to be involved. The multiple-criteria decision-making is both a social and a managerial task [FERRERO and ADRIANOV, 2021].

Resuming, Saaty method is about decomposing a decision-making problem into a hierarchy structure model, execute pairwise comparisons and establish priorities among the elements in the hierarchy structure, synthetizing judgements to generate a set of overall weights and checking the consistency of the specialist’s judgements [NOH, 2016; SAATY 2000; SAATY 2008].

3.1.1. Construction of Hierarchy Structure

According to Saaty [SAATY, 2008], to make a decision based on AHP method is needed to execute the following main steps:

A. Define the problem and determine the kind of knowledge needed;
B. Organize a decision hierarchy structure from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (usually are the alternatives or solutions to be evaluated);
C. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
D. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level is obtained.

The first step is to describe and identify the main goal or objective, then define evaluation criteria and sub-criteria based on specialists, literature, organization needs, and other requirements possibly applied.

The most important properties, common to (almost) all the MCA methods, which criteria should comply with, are listed as follows.

- Exhaustiveness: the set of criteria must cover all important aspects of the problem under consideration.
- Manageability: to avoid unnecessary analytical effort, the total number of criteria must be as limited as possible, and the value tree of objectives and criteria should not be more detailed than necessary.
- Understandability: analysts, decision-makers, and problem stakeholders and all the other parties involved in the process must have a shared understanding of the assumptions and concepts behind each criterion.
- Measurability: criteria must measure the performances of an option as precisely and clearly as possible, in a quantitative or qualitative way, compatibly with the characteristics of the nature of the measure under consideration.

- Non-redundancy: criteria that have been judged to be excessively similar to others must be excluded from the list.

Figure 12 shows a general hierarchy structure, adapted from [TRIANTAPHYLLOU, 2000; SAATY2001], for an example of hierarchy problem, that shows a resume of the problem that is needed to be solved. The first part shows the main objective and the goal that wants to be achieved, the second layers are the criteria that have been selected by literature and/or expert's judgements and evaluation. The third part, to avoid too many criteria with high number of pairwise comparisons, depending on the complexity of the problem, it is created a sub-criteria layer, with issues that need to be evaluated inside of each criterion. They will also have their weights evaluated by experts through pairwise comparisons. The last part shows the alternatives for the resolution of the problem or path to achieve the main goal.

The hierarchy structure is a multi-criteria evaluation system that consists of several levels including goal, evaluation criteria and its sub criteria, and alternatives for solution. This hierarchy structure is useful to aware a problem in systematic manner, and to achieve the evaluation goal in the top-level [NOH, 2016].

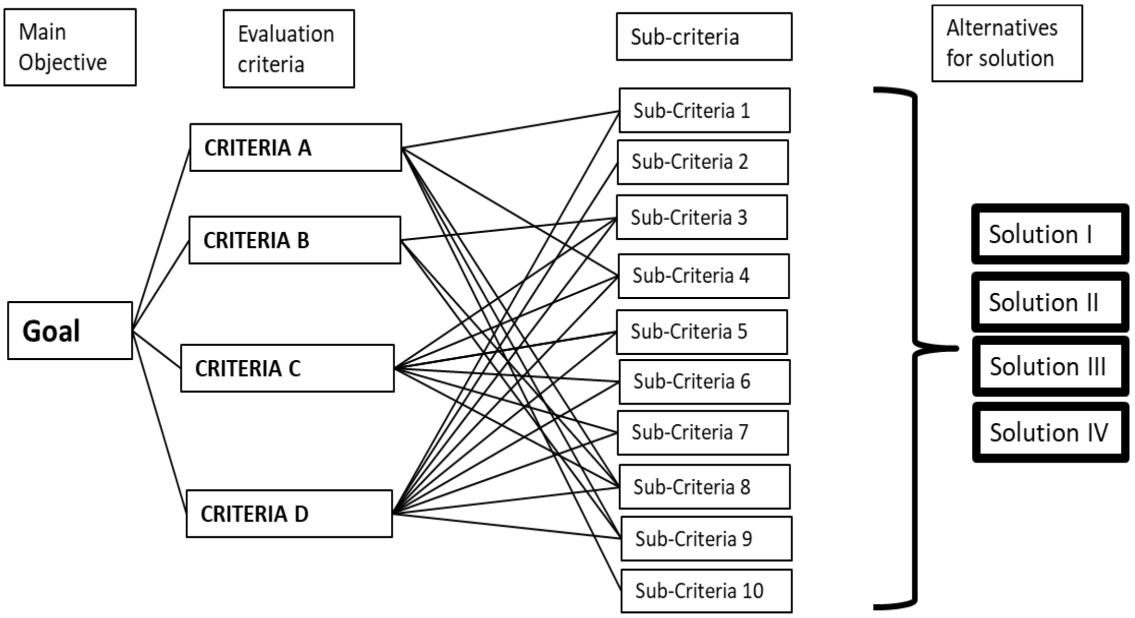

Figure 12 – General Four Level Hierarchy Structure

3.1.2. Selection of Specialists

The most significant contributors to improve consistency of the judgement are: (1) the homogeneity of the elements in a group, that is, not comparing a grain of sand with a mountain; (2) the number of elements in the group to improve consistency with the psychological experiments showing that an individual cannot compare simultaneously more than seven objects (plus or minus two) without being confused; and (3) the knowledge of the analyst about the problem under study that can influence the decision [SAATY AND VARGAS, 2001]. The group of judgments must be integrated one at a time carefully and mathematically, taking into consideration when desired the experience, knowledge, and power of each person involved in the decision.

In a problem decision involving multiple stakeholders, Saaty and Vargas have identified the main stakeholders that could impact the decision [SAATY AND VARGAS, 2001]. Although Saaty and Vargas emphasize the importance of the specialists, they do not go deep on how to perform their selection, and only mention that it is an important task and that having knowledge in the areas is important for the consistency of the research.

In [NOH. 2016] multicriteria evaluation, experts were selected by considering their expertise and experience on the matter of the backend nuclear fuel cycle, due to the importance in the policy decision making and the relevance of professional insights and experiences. Also, the study remarks that such important decision should come from a group of experts and not from one person. Noh emphasizes that in the case of decision-making procedure, especially in the public or national policies, the final decisions are made by key decision makers in high levels of an organization. Considering the complexity of matters, the decision makers would generally depend on various professional advice from experts in the fields. Noh have contacted 14 experts and received feedback from 12. Noh has only selected the experts according to their area of expertise, working years' experience, type of organization that he/she belongs and some comments and remarks about each one.

Schwenk-Ferrero and Andrianov, in their nuclear waste management strategies using MCDA, have used IAEA approach and judgements of relevant stakeholders, including technical experts, local authorities, neighboring countries and national and international groups. They have also emphasized that a crucial step in the decision aiding-process is the aggregation of the judgements about the alternatives' performances on each criterion which should faithfully model the overall preferences of both stakeholders and technical experts [SCHWENK-FERRERO and ANDRIANOV, 2017].

In [MAIA, 2022], to select the best site for near surface storage for reactor compartment in Brazil, it has been considered 18 experts, including Brazilian Navy, Amazul, Engepron, Eletronuclear, IAEA, CNEN and Nuclear Naval Agency. They were from nuclear area, naval, management and regulatory area, 17 with at least Master's degree (10 PhD) and 1 with Bachelor. Also, in similar use of the AHP methodology, [MARTINS, 2009] has used 8 specialists for her research, only specifying the area of experience and organization. Furthermore, Jato-Spino, in a MCDA model used to support the conservation of paramount elements in industrial facilities, has used the opinion of 26 experts, most of them with academic profile [JATO-SPINO et al, 2022].

In IAEA NG-T-3.20 it is emphasized that the decision support process begins with the identification of the decision maker's problem and an identification of group of subject matter experts and stakeholders. A stakeholder is a person who has an interest or a stake in the object being evaluated or decision to be taken. Individual stakeholders are likely to have different views on the problem, its surroundings and treatment. All stakeholders need to develop a common understanding of the problem and the objectives to be considered at the time the alternatives are evaluated [IAEA NG-T-3.20, 2019].

There is a conceit that the significance of expert competence consideration in a decision problem in a group is inversely proportional to the expert group size. So, consequently, after exceeding a certain expert group size, it is inappropriate to take expert competence into account. As a result of specific research, it was concluded that under maximal acceptable expert estimation error of 10% an expert group size of 30 experts would be the maximum number recommended to be used [TSYGANOK et al, 2012].

The AHP provides a means of decomposing the problem into a hierarchy of subproblems which can more easily be comprehended and subjectively evaluated. The subjective evaluations are converted into numerical values and processed to rank each alternative on a numerical scale [BHUSHAN and RAI, 2004]. For complex strategic decisions the expert group of formation should comply with decision-makers, subject matter experts, financial evaluation, and consultants [BHUSHAN AND RAI, 2004].

Thus, the experts' opinions can have a significant impact on deciding the domestic strategy for SNF management that are determined and promoted by the high-level governmental officers, and because of it, experts' opinion is considered in complex problems that need a national decision to move forward. This is a critical task, and because of it, the experts are required to cover not only in technical but in sociopolitical aspects of the SNF management, so the study tries to consider the experts with various academic backgrounds, expertise, and affiliations.

3.1.3 Criteria Pair-wise comparisons

The pairwise comparisons may use both qualitative (subjective opinions) and quantitative (by actual measures as weight, unit cost, size, etc.) values.

For the criteria pairwise comparisons, it is needed to scale numbers that indicate how many times a given criterion is more important or relevant than other being compared with. Table 6 [SAATY, 1980] exhibits the scale proposed by Saaty [SAATY 2008]. Thus, relative priorities or weights can be drawn in sequential comparisons [NOH, 2016]. The values of the comparisons will be given by specialists throughout a research spreadsheet to be filled by each one. With the results of the spreadsheet, a reciprocal matrix will be set.

Table 6–Fundamental scale proposed by Saaty for comparisons.

INTENSITY OF IMPORTANCE	DEFINITION	EXPLANATION
1	**EQUAL IMPORTANCE**	TWO ACTIVITIES CONTRIBUTE EQUALLY TO THE OBJECTIVE
2	WEAK OR SLIGHT	
3	**MODERATE IMPORTANCE**	EXPERIENCE AND JUDGEMENT SLIGHTLY FAVOUR ONE ACTIVITY OVER ANOTHER
4	MODERATE PLUS	
5	**STRONG IMPORTANCE**	EXPERIENCE AND JUDGEMENT STRONGLY FAVOUR ONE ACTIVITY OVER ANOTHER
6	STRONG PLUS	
7	**VERY STRONG OR DEMONSTRATED IMPORTANCE**	AN ACTIVITY IS FAVOURED VERY STRONGLY OVER ANOTHER; ITS DOMINANCE DEMONSTRATED IN PRACTICE
8	VERY, VERY STRONG	
9	**EXTREME IMPORTANCE**	THE EVIDENCE FAVOURING ONE ACTIVITY OVER ANOTHER IS OF THE HIGHEST POSSIBLE ORDER OF AFFIRMATION
RECIPROCALS OF ABOVE	IF ACTIVITY i HAS ONE OF THE ABOVE NON-ZERO NUMBERS ASSIGNED TO IT WHEN COMPARED WITH ACTIVITY j, THEN j HAS THE RECIPROCAL VALUE WHEN COMPARED WITH i	A REASONABLE ASSUMPTION
1.1 - 1.9	IF THE ACTIVITIES ARE VERY CLOSE	MAY BE DIFFICULT TO ASSIGN THE BEST VALUE BUT WHEN COMPARED WITH OTHER CONTRASTING ACTIVITIES THE SIZE OF THE SMALL NUMBERS WOULD NOT BE TOO NOTICEABLE, YET THEY CAN STILL INDICATE THE RELATIVE IMPORTANCE OF THE ACTIVITIES

The results of the comparisons for each criterion and sub-criteria are measured by values from 0 to 9 as shown in Table 4. Higher number means the element is considered more important than the other being compared with. In addition, this evaluated value satisfies the reciprocal condition: If A is evaluated as x times more important than B, then B is 1/x times more important than A. All comparisons are sequentially performed from the lowest level to the top level. Cognitive psychologists have recognized for some time that there are two kinds of comparisons that humans make: absolute and relative. In absolute comparisons, alternatives are compared with a standard or baseline which exists in one's memory and has been developed through experience. In relative comparisons, alternatives are compared in pairs according to a common attribute [SAATY, 2000; NOH, 2016]. The AHP has been used both types of comparisons to derive ratio scales of measurement.

The number of comparisons depends on the number of elements (n) thus, it is necessary to select proper elements to avoid performing too many comparisons. In practice, it is recommended that “n” is not over 8 to 10 for the reliable and consistent judgements without confusing [NOH, 2016]. The number of comparisons is equal to n(n-1)/2, where “n” is the number of criteria.

There are many situations where elements are equal or almost equal in measurement and the comparison must be made not to determine how many times one is larger than the other, but their fractional relative importance. In other words there are cases with relative importance factors between 1 and 2 and it is needed to estimate values such as 1.1,1.2,... 1.9 [SAATY, 2000].

When we have alternatives in which the choice-making situation has both costs and benefits associated with them, it is useful to construct separate costs and benefits hierarchies, with the same alternatives on the bottom level of each. Thus, one obtains both a costs-priority vector and a benefit-priority vector. The benefit/cost vector is obtained by taking the ratio of the benefit priority to the cost’s priority for each alternative, with the highest ratio indicating the preferred alternative. In the case where resources are allocated to several projects, such benefit-to-cost ratios or the corresponding marginal ratios prove to be very valuable [SAATY, 2000; TRIANTAPHYLLOU, 2000].

3.1.4 Matrix construction

The matrix derived from the criteria and experts' judgements is a tool for extracting the qualitative information from decision makers. After defining a list of criteria and alternatives to achieve the goal, it is built a judgment matrix $A = [a_{ij}]$that represents the value of the pairwise comparison of the i-th alternative (or criterion) with the j-th entity, as shown in Eq. (1).

The entry a_{ij}represents the intensity rate attributed by the experts (or decision makers). It reflects the preference between 2 alternatives (criteria or sub-criteria) pair by pair (it means the relative importance of $A_i$when compared with A_j, for all i ,j = 1, 2, …,n). Each alternative is denoted by $\{A_1, A_2, \cdots, A_n\}$,where n is the number of compared alternatives. As judgment matrices are reciprocal matrices, $a_{ii} = 1$ and $a_{ij} = {}^{1}/_{a_{ji}}$ [SAATY, 2005; NOH, 2016; TRIANTAPHYLLOU, 2000; MAIA, 2022].

$$A = (a_{ij}) = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{vmatrix} \tag{1}$$

3.1.5 Relative importance calculation of each criterion

The importance of the alternatives must be determined after the construction of each judgement matrix A. The matrix entry a_{ij} can also be represented by the ratios ${}^{w_i}/_{w_j}$ where W is defined as the vector of current weights $\{w_1, w_2, \cdots, w_n\}$ of the alternatives. As the judgment matrix is reciprocal, $a_{ii} = {}^{w_i}/_{w_i} = 1$ and $a_{ij} = {}^{1}/_{a_{ji}}$.

Therefore, the judgment matrix A can be expressed as a function of the vector W components, as described by Eq. (2):

$$A = \left({}^{w_i}/_{w_j}\right) = \begin{vmatrix} 1 & {}^{w_1}/_{w_2} \cdots & {}^{w_1}/_{w_n} \\ {}^{w_2}/_{w_1} & 1 \cdots & {}^{w_2}/_{w_n} \\ \vdots & \vdots \cdots & \vdots \\ {}^{w_n}/_{w_1} & {}^{w_n}/_{w_2} \cdots & 1 \end{vmatrix} \tag{2}$$

The alternatives relative importance can be calculated using different approaches, as: a) Calculating eigenvectors proposed by Saaty [SAATY, 1980] which provides a robust estimation and a verification of the overall consistency (selected method for this thesis due to its efficient consistency evaluation methodology); b) normalizing columns of Matrix A in Eq. (2), probably the simplest one, but relatively unstable; c) using geometric mean of Matrix A columns in Eq. (2), which presents some theoretical advantages: and d) use of the logarithmic regression method proposed by [LOOTSMA, 1993].

The eigenvector is a representation of the priorities described by the vector of current weights {W1 ,W2 ,⋯,Wn } of the alternatives. It is derived from the positive reciprocal pairwise comparison judgment matrix $A = [a_{ij}]$ when A is slightly perturbated by a consistent matrix [SAATY, 2002].

The eigenvector method derives ratio scales from principal eigenvectors [SAATY, 1980]. The eigenvector (w_i) calculation, derived from Eq. (2), is presented in Equation (3).

$$w_i = \left(\prod_{j=1}^{n} W_i / W_j \right)^{1/n} \tag{3}$$

The eigenvector normalization enables the comparison between criteria and alternatives. The normalized eigenvector is also called priority vector. The priority vector is the eigenvector of the matrix A, in the form of Eq. (2). Since it is normalized, the sum of all elements in the priority vector is 1. The priority vector shows relative weights among the alternatives being compared.

The eigenvector normalization is presented in Equation (4),

$$Ʈ= \left| \frac{w_1}{\sum w_i} : \frac{w_2}{\sum w_i} : \frac{w_3}{\sum w_i} \right| \tag{4}$$

The eigenvalue is calculated as the sum of products between each element of the eigenvector and the sum of columns of the judgment matrix A [SAATY, 1980]. Consequently, for the calculation of the maximum eigenvalue of the matrix λ_{max}, SAATY defines an auxiliary vector V, whose components are the sum of the elements in the corresponding line. Then, the resulting vector is multiplied with the vector W, as shown in equation (5),

$$\lambda_{\max} = V \times W \tag{5}$$

3.1.6 Consistency evaluation

Saaty AHP method also predicts consistency evaluation considering that the specialists, as humans' beings, have the possibility of not being consistent.

According to Saaty [SAATY, 1980], in a consistent reciprocal matrix, the largest eigenvalue is equal to the size of the comparison, i.e. $\lambda_{\max} = \mathrm{n}$. It gives a measure of consistency, which is called consistency index (CI), defined by Eq. (6).

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$$\mathrm{CI} = \frac{\lambda_{\max} - n}{(n-1)} \tag{6}$$

The consistency ratio (CR) allows to evaluate the inconsistency. CR is obtained by dividing the CI by the Random Consistency Index (RI), as shown by Eq. (7). The RI is an average random consistency index derived from a sample of size 500 of randomly generated reciprocal matrices with entries from the set (9, 8, 7, ..., 2, 1, 1/2, ... , 1/7, 1/8, 1/9). If the CR is 10% or less, the inconsistency is acceptable. Otherwise, the model or/and the judgments must be reviewed [SAATY, 2008]. Table 7 shows the Random Consistency ratios suggested by Saaty for different orders (n) of the judgment matrix A [Saaty, 2001]

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{7}$$

Table 7 – Random Consistency Ratio proposed by SAATY.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

4. Methodology

The main objective of this thesis is to propose and develop a methodology for Spent Fuel Management that allows to evaluate the best alternatives or solutions for the future of SF in Brazil that could also be applied in other countries, based in international best practices, experience, and evaluated by nuclear experts using Analytic Hierarchy Process technique. It has been developed following the bellow-mentioned phases:

A. Research Review with data collection and resume of good practices related to SF management, strategy selection, definition, and screening of the criteria to be used based in international experience, reviewed and validated by specialists. Also, with evaluation of weighting contribution factor of each criterion.
B. Strategy Scenarios screening and preliminary analysis (description of each viable strategy scenario, definition of each criterion and sub-criteria and its relations between each of them, with weights to each criterion and sub criterion, based on specialist's research spreadsheet
C. Specialists survey, consolidation, and output evaluation (Multicriteria Method Calculation and Evaluation)
    1. Preparation of the Survey and send it to specialists evaluation
    2. Resume the output of the specialists and evaluate the results
    3. Rank the strategy scenarios with the specialists' results and consistency check calculation
D. Scenarios Cost evaluation and comparison
    1. Quantitative cost estimation of the main scenarios
    2. Cost ranking and evaluation with the best strategy selected by the experts
    3. Combine both AHP and Cost Calculation results in order to have the best alternative selected

4.1. Research Review

This research of SF management methodology was based in international guides and papers regarding selection and ranking of the best strategy to be used in NPP´s country specific scenario as shown in section 2.3 (Multicriteria Decision Method Techniques) to propose a method to support the decision and evaluate the possible SF scenarios for Brazil case, that could also be used for other countries. Evaluation of the pre-selected criteria to be used and simplify them as much as possible to optimize the calculation of the matrix.

4.2. Methodology proposal

The first step the selection of the MCDM to be used. Then, after the selection of the MCDM path it is considered the international experience to select the recommended criteria and sub-criteria to be evaluated for each specific case.

Considering the AHP methodology and also IAEA [IAEA NG-T-3.20, 2019], EPRI methodology [EPRI, 2011 and EPRI 2014] research and international research papers [KIM et al., 20221, NOH, 2016; YOON et al, 2017; SCHWENK-FERRERO and ANDRIANOV, 2017] related to SF strategy it is realized that there are several ways to deal with MCDM and AHP method as well as regarding its criteria and sub-criteria definition. Some of them only evaluate the weighting relation until criteria level and goes to a measurable second layer [IAEA, 22019; YOON et al, 2016, EPRI, 2014 and 2011 and KIM, 2021], others perform the research until the second layer, developing sub-criteria together with their corresponding weighting factors [NOH, 2016, SCHWENK-FERRERO and ANDRIANOV, 2017]. None of them has done a complementary cost estimation to support the recommended option in terms of its financial viability.

The more comprehensive way to deal with such complex problem of SF management would be to combine weighting evaluations of specific key indicators for a cost estimative of main alternatives to be proposed. Also, as explained in section 2.3.2, it is recommended AHP method, although other methods could be also used to evaluate a complex and multicriteria problem as SF management.

Considering all these aspects and the international experience and best practices described in the previous sections, the proposed methodology, was structured based on the following steps:

a) Definition of the multicriteria decision problem / issue to be evaluated
b) Definition of possible alternatives to solve the problem or issue
c) Criteria and Sub-criteria definition based on international experience, under experts' validation
d) Construction of objectives tree considering the criteria, sub-criteria, and options of solution in a hierarchy model
e) Experts´ research and selection
f) Sensitivity analysis

g) Conclusions of the MCDM evaluation results
h) Cost evaluation of the main solution alternatives
i) Conclusion with the recommended solutions for SF management strategy

4.2.1 Definition of the multicriteria decision problem

Appropriate description of the SF management problem and possible solutions, with appropriate description of the country scenario, stakeholders, and all data related to SF consumption, strategy to support the research.

4.2.2 Definition of possible alternatives to solve the problem / issue

As mentioned in chapter 2.2.2 (Spent Fuel Management) there are 2 paths to be followed:

a) Closed Nuclear Fuel Cycle, where reprocessing of SF is used and then its waste is disposed as HLW.

b) Open Nuclear Fuel Cycler, where SF is disposed as soon as it reaches to specific cooling time and is transported to a final disposal.

Regarding disposal of SF or HLW, no country has a final geological disposal in operation, but France, Finland and Sweden are moving forward in its design and construction. Geological Disposal Construction is still a common issue to all countries and a challenge to nuclear energy industry. To mitigate that, countries as the United States are moving forward in the design and licensing of Interim Storages for SF until a political decision for final disposal is taken.

To select all alternatives for SF management, a combination of these paths must be evaluated to analyze each one based on selected criteria and sub-criteria. Section 2.2.2 (Spent Fuel Management) describes the different paths that could be followed regarding SF management, from Open Fuel Cycle until Closed Fuel Cycle, even with option of having another country to reprocess the own SF and then turn back as HLW.

4.2.3. Criteria definition and description

Selecting the main relevant criteria is critical for the evaluation of any problem based on a MCDM. According to [NOH, 2016], the criteria are required to balance each aspect for the strategy selection, as technical and engineering versus social and political, with a qualitative and quantitative evaluation.

Also, to avoid answering too many pair-wise comparison in the AHP survey, it is necessary to limit the number of evaluation criteria as a reasonable level. It is usually recommended not to exceed ten criteria in each level of AHP structure [NOH, 2016]. Most of other authors, are more restrictive with the number of criteria, as it may lead to inaccurate judgements and due to the increase of comparisons needed when is selected more than seven criteria [KUMAR et al, 2016, RAMANATHAN and GANESH, 1995; MILLET and HARKER, 1990; ZLAUGOTNE et al., 2020; MARTINS, 2009; MAIA, 2022].

Also, it is mentioned by [MARTINS, 2009] that in complex problems decision, not all criteria are so objective as economical and engineering criteria. There are some criteria more subjective, as social impact, safety and environmental that are not easy to be measured and that´s because the judgement of the experts and multiple stakeholders is important during a decision-making process [MARTINS, 2009].

The criteria quantity should be as simplified and small as possible, to reduce the stress of the judgements and data collection, optimizing the process, considering that for "n" criteria or sub-criteria, the total number of comparisons will be $n(n-1)/2$. [KUMAR et al, 2016, RAMANATHAN and GANESH, 1995; MILLET and HARKER, 1990; ZLAUGOTNE et al., 2020; MARTINS, 2009; MAIA, 2022].; KEENEY et al, 1993].

Considering the recommendations described, seven criteria have been chosen in the study, as a limiting number of criteria or sub-criteria associated to a specific criterion. This is a general recommendation after analyzing several literatures regarding SF management and reduce the risk of human errors in the pairwise comparisons.

As mentioned in section 2.3.1.1 and 2.3.1.2 respectively, IAEA has reached to the following criteria selection for evaluating NFC strategy [IAEA NG-T-3.20, 2019]: Economics, Environmental, Social, Institutional Aspects and other aspects related specifically to the country and EPRI [EPRI, 2011] have used Sustainability of fuel Supply, Proliferation Resistance and Security, Waste Management, Fuel Cycle Safety and Economic Competitiveness.

[KIM et al, 2021] have reached to the following criteria, after similar research: Technology (Safety and Resource utilization), Environmental Impact, Economics, Sociality and Institutional. NOH [NOH, 2016] has used Sustainability of fuel Supply, Proliferation Resistance and Security, Waste Management, Fuel Cycle Safety, Economic Competitiveness. Table 8 resumes the main criteria used in chapter 2.3.3 according to international experience.

Table 8 – Criteria evaluation based on international literature

	CRITERIA USED
NOH, 2016	Technology, Nuclear Safety, Nuclear Security and nonproliferation, Environmental Impact, Economics, Domestic Acceptance, and multilateral acceptance
KIM et al, 2021	Technology, Environmental Impact, Economics, Sociality and Institutional
IAEA NG-T-3.20, 2019	Economics, Environmental, Social, Institutional Aspects and other aspects related specifically to the country
EPRI, 2011/2014	Sustainability of fuel Supply, Proliferation Resistance and Security, Waste Management, Fuel Cycle Safety, Economic Competitiveness

Considering the mentioned main criteria used in several international literature, and putting all of them together we have the following common criteria: Nuclear Safety, Security and nonproliferation, Environmental Impact, Economics. Most of the authors has also included as criteria Waste Management, Technology, public acceptance and sustainability of fuel supply and country specifics.

To optimize the calculation, it is recommended to merge Environmental Impact with Waste Management. Country Specifics includes as sub-criteria the “Maturity of Technology” and “public acceptance”. Sustainability of fuel supply were considered, as the main objective is not to evaluate the capacity of manufacturing nuclear fuel. So, the following criteria were stablished Safety “**C1**”, Environmental Impact and Waste Management “**C2**”, Nuclear Security & Nonproliferation “**C3**”, Economics “C4”, and Country Specifics “**C5**” as starting point to this research.

These criteria selection should be evaluated by specialists’ consultancy to validate the criteria selected.

4.2.4 Sub-criteria definition and description

The sub-criteria definition will use the same approach of criteria definition. Sub-criteria are set to evaluate the relative importance of criteria.

IAEA [NG-T-3.20, 2019] does not go until the sub-criteria evaluation, but uses directly measurable key performance indicators (KPI) as lower criteria in the method calculation. Some of the KPI (related to ~~c~~riteria) are:

- Safety criteria related: core damage frequency, release frequency, frequency of individual effective dose at site boundary, source term, dose versus distance curve.
- Economics criteria related: Levelized unit electricity cost (LUEC), aspects that affect the total cost over systems commissioning, operation and decommissioning, net present value, total discounted cost, internal rate of return, discounted payback period and overnight capital costs and cash flow.
- Waste Management criteria related: RW volume produced, radioactivity by time, HLW volume.
- Proliferation resistance and physical protection criteria related: high quality safeguards implementation (increasing extrinsic proliferation resistance), ‘safeguards implementation considered from early design stage’ and bilateral cooperation agreement obligations, with non-proliferation assurances documented.
- Environment criteria related: quantity of useful energy produced by system per unit of mined natural uranium/thorium; the supply sufficiency of identified rare non-nuclear materials for a targeted deployment scale; and the amount of other consumables used, or land impacted per unit of useful energy produced.
- Maturity of technology related: application for a reasonable length of time, design stages (feasibility study, conceptual design, basic design, site selection, detailed design, pre-licensing).
- Country-Specific criteria related: Infrastructural (legal, institutional, industrial, human resource) capabilities, political support and public acceptance issues, flexibility for non-electrical services and energy products, and load following capability.

In EPRI [EPRI 2011, 2014] research, the following sub-criteria have been used:

- Sustainability of fuel Supply criteria related: Minimizing Uranium Utilization, Managing/Optimizing Plutonium Inventory.
- Proliferation Resistance and Security criteria related: not applicable.
- Waste Management criteria related: Minimizing LLW, minimizing Repository Waste (HLW), Minimizing public exposure during routine activities.

- Fuel Cycle Safety criteria related: Minimizing occupational radiological exposure during operations, minimizing calculated consequences of potential accidents, minimizing capital costs.
- Economic Competitiveness criteria related: Minimizing Fuel, operations and maintenance costs, status development and deploying the technology, application, and status of existing licensing framework for the technology.

[NOH, 2016] has used the following sub-criteria:

- Technology criteria related: Availability, Suitability, Accessibility.
- Nuclear safety criteria related: System resilience, accident tolerance, accident in transportation.
- Nuclear security & non-proliferation criteria related: Physical protection, nuclear proliferation resistance, compliance to international regime/norm.
- Environmental impact criteria related: radiological impact and non-radiological impact.
- Economics criteria related: Internal cost, cost of social conflicts, environmental cost.
- Domestic acceptance criteria related: Public acceptance and political support.
- Multilateral acceptance criteria related: multilateral identity, intention for hosting, possibility of institutionalization (all related to facilities shared with other country).

[KIM et al, 2021] has not used a second layer of sub-criteria, but measurable criteria as IAEA:

- Safety criteria related: Radiation exposure dose rate and waste toxicity level.
- Resources utilization criteria related: Uranium per energy generated.
- Environmental impact criteria related: HLW amount, LLW amount, Land use.
- Economic feasibility criteria related: Levelized cost of electricity, investment cost.
- Proliferation resistance criteria related: Amount of nuclear material and utility function value for facility detection.
- Public acceptance (social aspect) criteria related: Support fund.

The consulted references describe the previous sub-criteria as follows:

- Safety: It is the priority for this evaluation, and the main concern in nuclear industry. When speaking about safety, resilience and operation and transport concerns raises in mind as the main three issues that can be pointed out. Also, it is relevant to safety general transportation, radiological impacts, non-radiological impacts, internal costs, and public acceptance and political support. [IAEA NG-T-3.20; IAEA SSG-77, 2022; NOH, 2016; SCHWENK-FERRERO and ANDRIANOV, 2017].
- Environmental Impact and Waste Management: It is unquestionable that HLW and SF generated in a nuclear process will have environmental impact and will have to be managed. SF and RW inventory produced, transportation, radiological consequences and non-radiological consequences would be the main concerns when speaking about the environmental and waste management impacts [IAEA NG-T-3.20; IAEA NW-G-1.1, 2009. NOH, 2016; SCHWENK-FERRERO A. and ANDRIANOV A, 2017].
- Nuclear Security & Nonproliferation: They are critical to make sure that physical protection and safeguards of SF will be maintained and considered in the strategy selection. Looking into security and safeguards perspective, it is also important to care about accidents toleration in transportation, SF and RW inventory increase, radiological consequences of any accident and how to mitigate its effects with security and safeguards planning and preparations, as they can lead to a missing control of nuclear material. [IAEA NG-T-3.20; IAEA NW-G-1.1, 2009; OSTI, 2016; Noh, 2016; SCHWENK-FERRERO A. and ANDRIANOV A, 2017].
- Economics: the costs used in nuclear industry must be considered and must be considered. Costs are divided in Internal and External costs. Internal cost means any expenditures directly used including construction, operation, and maintenance (Internal cost), while external costs cover additional outcomes for accidental risk, policy and post processing [NEA-OECD, 2003]. Also, the costs could be impacted by the amount of SF/RW produced, transportation, physical protection measures, socioeconomic impacts, availability, and accessibility of the needed technology. [IAEA NG-T-3.20; NEA-OECD, 2003; Noh, 2016; SCHWENK-FERRERO A. and ANDRIANOV A, 2017].
- Country Specific´s: Sub-criteria are identified and analyzed, including the maturity of the technology of the country considering the SF strategy that is selected to be followed. Commonly used sub-criteria are: social economic

impacts, public acceptance and political support, availability/suitability and accessibility of the technology [IAEA NG-T-3.20; NOH, 2016; SCHWENK-FERRERO and ANDRIANOV, 2017].

After the analysis and integration of the described international experience, the following sub-criteria has been stablished for the present research work:

Safety related sub-criteria: System resilience proposed by KIM was integrated with reliability (considering the fact of the importance of the chosen strategy be reliable and safe with operational experience), being considered as “System Resilience & Reliability” **SC1**, “Accident tolerance in Operation” **SC2** (evaluating accidents during operation and its frequency of occurrence) and “Accident tolerance in Transportation” **SC3** (very important due to the need of transport of SF inside the country and outside of it when decided to be sent for external reprocessing). Additionally, they could be measured by availability of operation, frequency of accidents during operations and transport respectively.

Environmental & Waste Management sub-criteria: “SF and RW inventory impact” **SC4** (considering the reduction as much as possible of the impact for future generations), “radiological impact” **SC5** and “non-radiological impact” **SC6** (risks associated to the operation). Additionally, they could be measured by SF and RW produced, HLW produced, occupational radiological exposure and radiotoxicity through time.

Nuclear Security & Proliferation Resistance sub-criteria: “Physical protection” **SC7** (to secure the nuclear material and the protection against theft or any other way to increase the probability of having risk of nuclear material stolen), “Nuclear nonproliferation & safeguards” **SC8** (Compliance to international regime and norms and commitments signed). It was included “Transportation Risk” **SC9** [SCHWENK-FERRERO and ANDRIANOV, 2017]. t could be measured by security fragility, compliance with the commitments signed and by distance of transportation which would increase the risk in the activity.

Economics: “Construction and Operational & Maintenance (O&M)) Cost” **SC10** (these costs have to be evaluated as the strategy must be feasible and justified), “Environmental Cost” **SC11** (value for the environment and treatment of SF and RW), also the “socioeconomic impacts” **SC12** (as the neighborhood will be affected according to the decision to be taken), and long term-commitment, suggested by [SCHWENK-FERRERO and ANDRIANOV, 2017] (as the strategy will be for a long-term planning, with several stakeholders, possibly another country to support the activities). They could be measured by levelized unit electricity cost, O&M cost, and decommissioning cost.

Country Specific´s – “Public acceptance and political support” **SC13** (different from country to country, they have to be evaluated as public and political issues may corrode the strategy as they have strong impact in the country strategy), “Technology Availability/Suitability/Accessibility” **SC14** (as the technology has to be safe, available and accessible and adequate for each specific reality), “Infrastructure” **SC15** (the specific country structure has to be evaluated in order to receive new technologies and activities as e.g. SF and HLW transport) and “Long term commitment and development” **SC16** (SF strategy is a long term strategy and through generations and it has to be taken into account).

The relation between each criterion and sub-criteria is shown in table 9. The table easily shows all the areas that will be evaluated and ratified by specialists. Also, the table enables to easily build the schematic hierarchy structure for this case.

This sub-criteria selection should be evaluated by specialists’ consultancy in order to validate the criteria selected.

Table 9 – Criteria x sub-criteria evaluation

CRITERIA	SUB-CRITERIA	System Resilience & reliability	Accident Tolerance in Operation	Accident tolerance in Transportation	SF and RW inventory impact	Radiological Impact	Non-Radiological impact	Physical Protection	Nuclear nonproliferation & safeguards	Transportation risk	Construction and Operation & Maintenence Costs	Environmental Cost	Socioeconomic impacts	Public acceptance & Political Support	Technology (availability/Suitability/accessibility)	Infrastructure	Long term commitment and
		SC1	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**	**SC7**	**SC8**	**SC9**	**SC10**	**SC11**	**SC12**	**SC13**	**SC14**	**SC15**	**SC16**
Safety	**C1**	X	X	X													
Environmental Impact & Waste Management	**C2**				X	X	X										
Nuclear Security & Nonproliferation	**C3**							X	X	X							
Economics	**C4**										X	X	X				X
Country Specifcs	**C5**													X	X	X	X

4.2.5. Construction of objectives tree considering the criteria, sub-criteria, and options of solution

After listing all the criteria and sub-criteria, it is needed to build the AHP criteria x sub-criteria hierarchy tree structure, with the main objective and the pre-selected alternatives for the problem to be solved [TRIANTAPHYLLOU, 2000; SAATY 2001]. Figure 14 illustrates the General Hierarchy Structure recommended according to the criteria and sub-criteria listed in the previous chapters. This hierarchy tree is before the specialist's evaluation and still can be improved with their opinion.

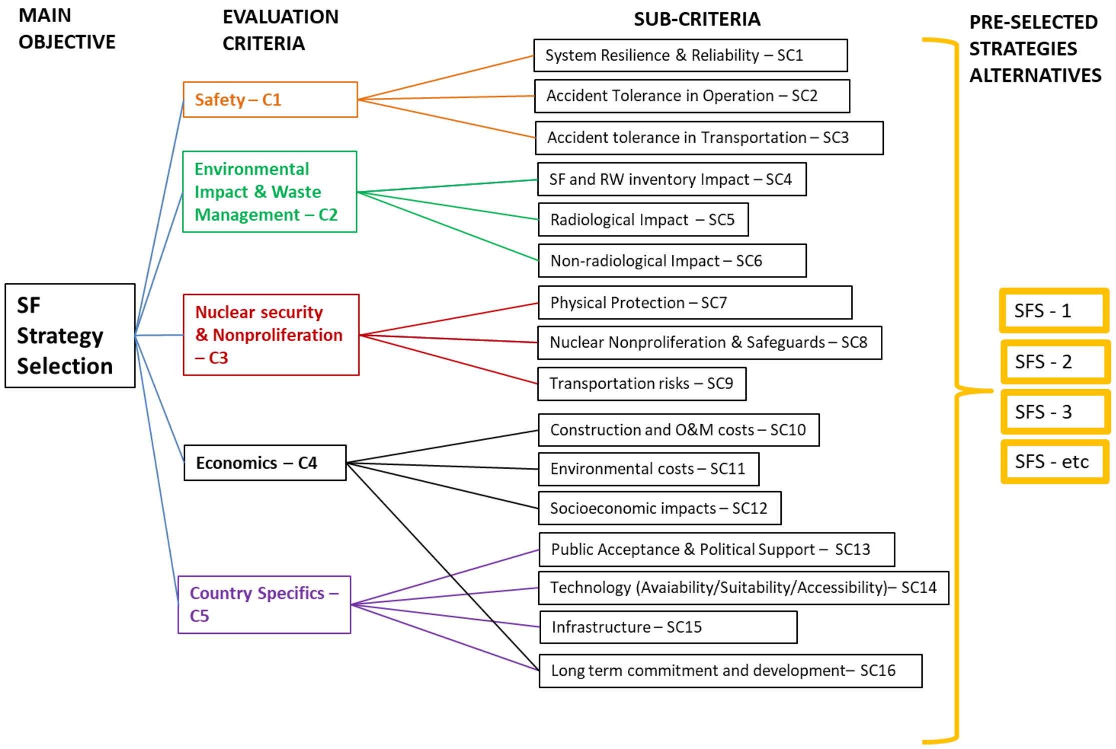

Figure 13 – General Hierarchy Structure recommended

4.2.6. Experts research and selection

As described in section 3.1.2. the specialist's selection should be based in a stakeholder´s selection based on their role around the problem which is being studied and requires a solution and a decision-making recommendation.

For a complex decision-making procedure, especially regarding national policies, the final decisions are usually taken by key decision makers in high levels of the organization. Considering the complexity of Spent Fuel Management to a country, the decision-makers depend on various professional advice from experts in the fields. That is, the professional experiences and understandings on the issue considered can serve as a basis for decision-making process. Thus, the experts' opinions can have a significant impact on deciding the domestic strategy for SF management that are determined and promoted by the high-level governmental leaders. That is the reason that expert survey has been considered as a key aspect for evaluating the main topic of this research.

Saaty, which is the one that have introduced the AHP method [SAATY, 1980; SAATY AND VARGAS, 2001] does not go very deep in the specialist selection, and does not recommend a minimum number to be followed, but emphasizes the importance of:

- ✓ experience, knowledge, and power of each one.

[NOH, 2016] research was done by 12 experts and has considered as important factors the following ones:

- ✓ Expertise, experience, and power with a decision-making role
- ✓ Type of organization

[SCHWENK-FERRERO and ANDRIANOV, 2017] have emphasized the importance of having relevant stakeholders as specialists, including:

- ✓ technical experts, local authorities, neighboring countries, and national and international groups

The previous characteristics were also mentioned by [BHUSHAN and RAI, 2004], adding the importance of financial analysis and specific consultants.

[MAIA, 2022], in a recent use of AHP for site selection of RW repository, has considered 18 experts in its research considering the following specialists and stakeholders, with the following aspects:

- ✓ 10 PhD, 10 MSc and 1 bachelor
- ✓ Divided in nuclear, naval area, management and regulatory.

[MARTINS. 2009] has used 8 specialists only specifying their experience and organization, and Jato [JATO-SPINO et al, 2022], has used 26, but must of them with academic profile. Both have not used a complete range of stakeholders, probably due to the difficult to access different levels of these stakeholders, as recommended by other authors and IAEA [IAEA NG-T-3.20, 2019].

Another important issue is related to the number of experts. It is not recommended more than 30, as the significance of the expert will decrease. So, for this research, it will be recommended to not exceed this number of experts.

Thus, it is recommended in this proposal, to have the relevant number of stakeholders involved, with experience background (of at least 10 years), recommended MSc or PhD degree or working as decision-making person with power of decision. Looking into SF strategy, the following stakeholders are recommended: Nuclear Regulator, Environmental Regulator, NPP owner, Neighborhood, Political related, Academic, Financial, international organizations, and military.

4.2.7. AHP method calculation

As described in session 3.1.3, after collecting the results of all the experts, the data will have to be calculated, as described in section 3.1 (Analytic Hierarchy Process Method) with a sensitivity analysis with the consistency check.

It has been prepared and used an Excel spreadsheet to do all the calculation, after all judgement data collected from the experts.

4.2.8. Conclusions of the MCDM evaluation results

After the calculation of the AHP, the results are analyzed and the alternatives for solution representing best alternatives for the problem identified. The best options should have the calculation cost evaluated as described in section 4.2.9.

4.2.9. Cost estimate of the main solution alternatives

To complement the evaluation of the SF management strategies it is crucial to have an estimative of cost of the main alternatives, considering most of all the criteria related, volume of SF generated, technology, geography, geology, etc. Over the years, different studies were performed to estimate the cost of spent fuel management in the nuclear fuel cycle. Closed nuclear fuel could have several economic advantages over direct disposal, as it would reduce spending on newly produced uranium fuel and extend the useful life of uranium resources. It would save money on long-term storage and disposal, and O&M costs, by reducing the size of the storage and repository necessary to handle spent nuclear fuel or by delaying the need to expand such a facility in the future enabling a cost-effective operation. On the other hand, reprocessing would also have economic disadvantages, considering the need of developing reprocessing technology and the development of partnerships with other States and organizations to use existing reprocessing plants.

After reviewing specific literature, it is clear how challenging is to perform a cost estimate of the back-end fuel cycle, due to different assumptions and considerations that have to be made for it. Some of these assumptions are the discount rate, types of waste, nuclear fuel cycle choice, lack of country radioactive and spent fuel management decision, country specific policies, regulations, and strategies, etc., increases the uncertainties of the calculations [JONUSAN, 2021; RODRÍGUEZ-PENALONGA and MORATILLA-SORIA, 2019; EASAC, 2014; CBO, 2007].

4.2.10. Conclusion of the more recommended solutions for SF management strategy

After the expert's evaluation using AHP MCDM and with the cost estimate of each of the main alternatives It is possible to reach to a conclusion and recommendations.

This research has the objective to rank the best SF management strategies for one country in a long-term planning and commitment, to provide enough information for decision-makers to follow the more recommended path to follow, based on stakeholders and specialists' opinions, combined with financial calculation and support.

5. Application case: Brazil SF Management Strategy Evaluation

This study aims to consider the issue of SF management and how to deal with the SF to have the nuclear industry sustainable, which is a critical aspect to support nuclear power industry in reaching its development in Brazil predicted by [EPE, 2021] with additional 8 GW from nuclear source until 2050, in addition to its Angra 1 and 2 NPPs in operation and Angra 3 under construction.

5.1. Definition of the multicriteria decision problem and Brazil SF Management scenario

Nowadays Brazil has two operating NPPs, Angra 1 and 2, with approximately 2 gigawatts (GW) of nuclear energy production, and third NPP at the same site, Angra 3, under construction with 67% of civil scope executed, with 1,4GW design, and it is planned to be operating until 2028 [ELETRONUCLEAR, 2022; CNN, 2021]. Brazilian National Energy Plan 2050 (PNE 2050) plans to install between 4GW to 8GW of nuclear energy until 2030 and 8GW to 10GW until 2050 [EPE, 2021]. Therefore, the country needs a National Spent Fuel Policy and Strategy to keep nuclear energy development and growth.

Besides that, Brazil has still not come into a decision about SF strategy of direct disposal or reprocess [CNEN, 2017] and the need of a detailed study and evaluation of how to deal with SF is increasing and extremely important for the future generations and to support nuclear energy development in the country.

Brazil needs to decide which path to take, considering direct disposal, long term storage and reprocessing options to keep growing with the nuclear energy and technology in the country.

5.1.1 Spent Fuel and HLW Management in Brazil

Brazil only produces SF due to its NPPs energy production and does not reprocess SF, therefore there is no HLW due to SF reprocessing. Brazil is committed with international safeguards and nuclear safety management in the country, with peaceful use of nuclear technology, as secured by Law 10.308 [BRASIL, 2001] and also by signature of the Joint Convention on the Safety of Spent Fuel Management[1] and on the Safety of Radioactive Waste Management since 1997, complying with the objectives of the convention, with the safe management of SF and RW [CNEN, 2017].

As mentioned in section 1.3, Brazil still did not reach to a national conclusion regarding the future of Spent Fuel in the country and has the strategy to keep it in safe condition, until the final decision about reprocessing or disposing it is taken, due to the huge amount of energy inside each SF [CNEN, 2017].

Law 10.308 [Brasil, 2001] establishes that CNEN is the responsible for the destination of RW produced in national territory. There is no planned geological disposal construction for the next years in Brazil, and according to Eletronuclear, it is planned to be built by CNEN until 2040 [ELETRONUCLEAR, 2017].

5.1.2 Spent Nuclear Fuel Produced in Brazil Forecast

Nowadays Brazil has only 2 operating NPPs, with Angra 3 planned to start its operations until 2028 [ELETRONUCLEAR, 2022]. It is also considered that 8 additional new NPPs will be constructed until 2050 [EPE, 2021] to attend EPE planning.

Angra 1 is started operating in 1985, initially with 40 years of lifetime (with initial planned shutdown to 2024). In 2019, as required by CNEN, Eletronuclear have applied a Long-Term Operation (LTO) request of 20 additional years [ELETRONUCLEAR, 2019], that will lead Angra 1 to operate until 2044.

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1 - The Joint Convention is the first legal instrument to address the issue of spent fuel and radioactive waste management safety on a global scale, created by IAEA. It does so by establishing fundamental safety principles and creating a similar "peer review" process to the Convention on Nuclear Safety. It has been adopted since 1997 and entered into force in 2001. The Convention applies to spent fuel resulting from the operation of civilian nuclear reactors and to radioactive waste resulting from civilian applications. It also applies to spent fuel and radioactive waste from military or defense programs if such materials are transferred permanently to and managed within exclusively civilian programs, or when declared as spent fuel or radioactive waste for the purpose of the Convention by the Contracting Party concerned. In addition, it covers planned and controlled releases into the environment of liquid or gaseous radioactive materials from regulated nuclear facilities. [IAEA, 2022]

5.1.2 SF production forecast for Angra 1, Angra 2 and Angra 3

Nowadays Brazil has only 2 operating NPPs, with Angra 3 planned to start its operations until 2028 [ELETRONUCLEAR, 2019]

According to CNAAA decommissioning Plan for Angra 1, Angra 2 and Angra 3, it is assumed to have a 20 years of Life extension of each NPP. Considering 20 years of LTO, the prediction of 2095 SF for Angra 1, 2873 SF for Angra 2 and 2845 SF for Angra 3, resulting in 7813 SF for the CNAAA site [ELETRONUCLEAR, 2019].

The graphic in figure 14 [ELETRONUCLEAR and BURSCHEID, 2019] shows the SF forecast for Angra 1, 2 and 3, and the necessity of casks considering SF production until end of operation of each NPP. The total number is a little higher conservative assumption for the calculation at the time of the graphic. In this study, it will be considered a total amount of 7813 SF assemblies resulting from the operation of the 3 NPPs, for calculation purpose. It is important to emphasize that if there is no decision regarding SF future, it will be needed to build another dry storage at CNAAA in a few years, with a higher capacity as it will have to include the SF in Angra 1 and 2 SFP when the decision to final shutdown the plant be taken, as well as for Angra 2, and later Angra 3. After 2045, 2063 and 2085 it will have an increase of SF as the NPPs are planned to be shutdown and SF will have to be removed and stored out of the plant.

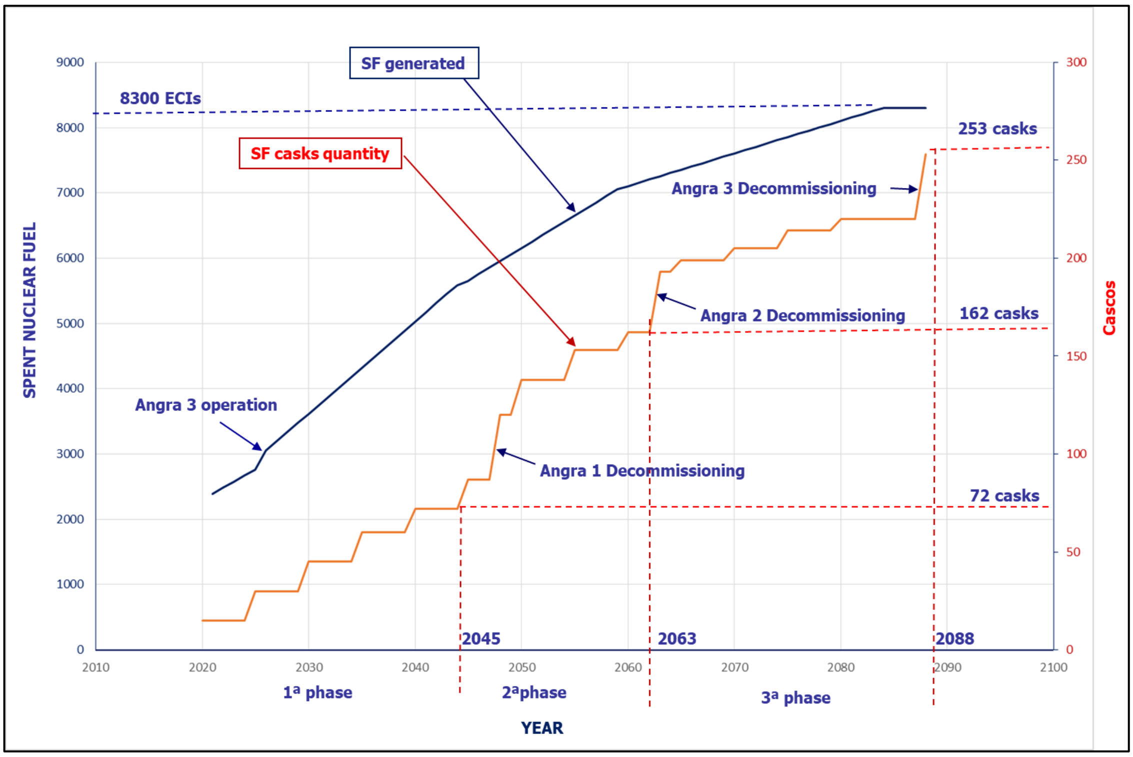


Figure 14 – SF forecast for Angra 1, Angra 2 and Angra 3 NPPs

5.1.3 SF production forecast for additional 8 GW from nuclear source

There are several types of different of nuclear reactor today, with different technologies. When speaking of 8GW, depending on the power of each unit, it could be built from 6 to 8 NPPs to reach this planned capacity [ELETRONUCLEAR, 2019].

Considering future NPPs technology for Brazil, Eletronuclear has already studied different types of reactors for new sites in Brazil, and is considering the Westinghouse AP1000, as well as the Areva-Mitsubishi Atmea-1 and Atomstroyexport's VVER-1000. [WNN, 2015].

For this thesis purposes, it will be assumed that the next 8 NPPs predicted in Brazilian Energy Strategy Plan, PNE 2050 [EPE, 2020], will be Westinghouse (WEC) Technology (although the methodology could be used for any type of technology) due to the following reasons:

1. Westinghouse has a long-term relation with Eletronuclear since construction of Angra 1 and is providing technical support with the projects related to Angra 1 long term operation licensing program.
2. Brazil already has other multilateral agreements with as a partnership with Indústrias Nucleares do Brasil (INB) on fuel and manufacturing technologies [WNN, 2015].
3. AP1000 have already 6 operating or under construction plants in China and USA.
4. WEC has experienced and well stablished nuclear technology through the years.
5. AP1000 is a PWR NPP, technology which is well known in Brazil and follow the same approach as Angra 1 and 2 NPPs.
6. U.S. Nuclear Regulatory Commission certificate.

WEC AP1000 is a NPP PWR reactor, based on nearly 25 years of research and development and has in its design 2 Steam Generators that uses a simplified, innovative and effective approach to safety and passive cooling technology. The AP1000 NPP has a gross power rating of 3.415 megawatt thermal (MWt) and a nominal net electrical output of 1.110-megawatt electric (MWe), with a 157-fuel-assembly core, 18-month fuel cycle and Sixty-year design lifetime [Westinghouse, 2023]. Spent fuel pool storage capacity is for 889 fuel assemblies [U.S.NRC, 2019].

For calculation purpose, the number of fuel assemblies refueled will be considered conservatively as the worst case of an 18-month fuel cycle plus 5 defective fuel assemblies (69 total assemblies or 44% of the core) as shown in AP1000 Final Safety Evaluation Report Related to Certification of the AP1000 Standard Plant [U.S.NRC, 2019].

5.2 MCDM method - AHP

As mentioned in chapter 2.3.2 (MCDA Method Selection), due to several reasons and based on international references, it has been selected the AHP method as the more adequate and used MCDM.

The criteria and sub-criteria used has been selected in section 4 and will be described in section 5.4.

5.3 Definition of possible alternatives to solve the problem / issue

Based on international experience, OFC and CFC are the possible main envisaged strategies to ensure safety and cost efficiency [IAEA NW-T-1.14, 2022]. Considering the possibility of 8-10GW for nuclear energy planned in PNE 2050 [EPE, 2022], what would significate 8 more NPPs (with sizes near to Angra 2 and 3) as well as the opposite situation of these increase of nuclear power generation not proceed due to political and financial reasons, it will be analyzed 2 main possible scenarios, the first one (A) with Angra 3 conclusion, together with the operating Angra 1 and 2 NPPs, that would be the more realistic scenario at the moment, and the second scenario (B) more optimistic, with the perspective of 8 more NPPs. It will also be considered, that if only Angra 1/2/3 NPPs are in operation, no Interim storage will be, due to the smaller volume of SF considering the existence of enough space in the site for local SF storage. Also, it is important to remind that although reprocessing have its difficulties, the process reduces the volume of SF and RW generated, and even sending the SF for reprocessing out of the country, possibly losing the “energy inside the SF”, it has the benefit of saving money of SF storage and new constructions to keep the SF safe.

Considering main scenario “A”, 3 paths could be possible: (i) OFC with directly SF disposal, after some years of storage to allow decay (SF strategy 1 - SF1); (ii) a second strategy would be to move forward to internal reprocessing, what would request internal technology development and HLW generated with reduction of SF volume (SF2);

(iii) the third strategy would be also reprocessing SF externally in another country, due to lack of technology and with HLW resulting returning to the country for disposal (SF3).

Considering scenario “B”, 4 paths could be possible: (iv) OFC, similar to (i), with directly SF disposal after some years of storage, but with higher SF volume (SF4); (v) OFC with SF directly to disposal, as the previous one, with previous years of storage, but as higher volume of SF, considering a centralized storage for SF to support the NPPs (SF5); (vi) CFC, similar to (ii), with internal reprocessing development, with higher volume of SF to be handled; (vii) CFC, similar to (iii), but with higher volume of SF, with all SF being reprocessed in external company and returning HLW for disposal.

Based on these 2 main scenarios considerations, the following SF strategies alternatives have been identified and have been evaluated together with criteria and sub-criteria, by specialists, as follows:

A. Angra 1/2/3 without need for Interim Storage
    i. Open Fuel Cycle – SF directly to disposal after storage of several years at CNAAA site and then sent to disposal (SF1)
    ii. Closed Fuel Cycle – SF being reprocessed internally and then sent to disposal (SF2).
    iii. External Closed fuel Cycle – SF storage at CNAAA site, reprocessed in another country with the RW being sent back for disposal (SF3)
B. Angra 1/2/3 + 8 additional NPPs
    iv. Open Fuel Cycle – SF directly to disposal after storage of several years at CNAAA site and then sent to disposal (SF4)
    v. Open Fuel Cycle – SF directly to disposal after storage of several years at CNAAA site and then sent to a centralized storage and then sent for disposal (SF5)
    vi. Closed Fuel Cycle – SF being reprocessed internally and then sent to disposal (SF6)
    vii. External Closed fuel Cycle – SF storage at CNAAA site, reprocessed in another country with the RW being sent back for disposal (SF7)

Although Internal Closed Fuel Cycle (SF 3 and 6) would be with very difficult to be implemented in Brazil due to technology and due to safeguards restrictions, it has been kept in the options to verify its feasibility in the expert’s opinion.

Figure 15 shows the main Strategies selected for this thesis for Brazil scenario´s.

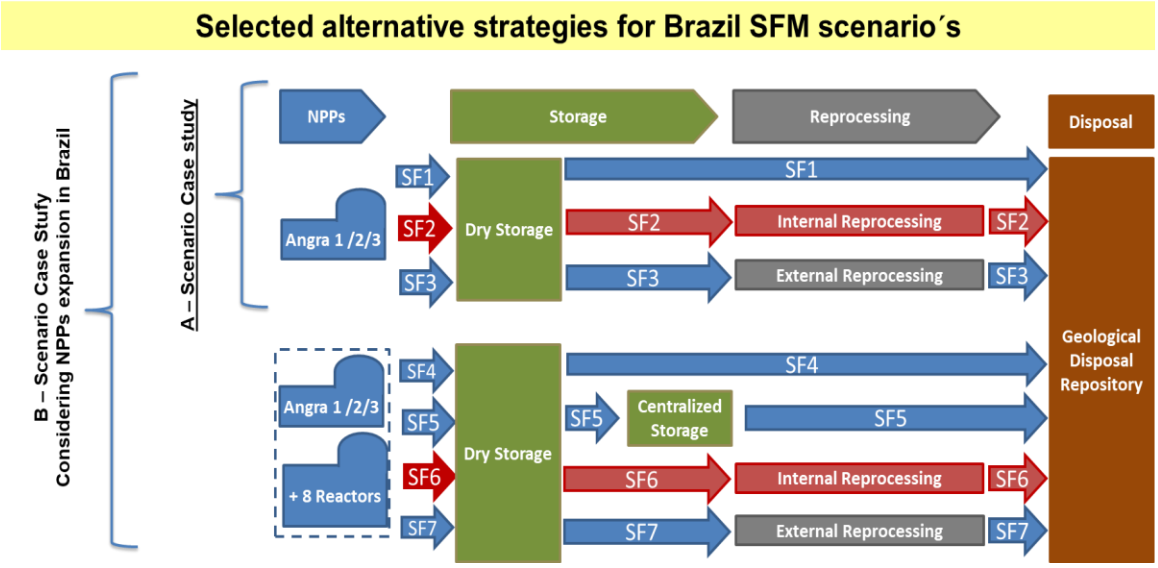


Figure 15 – SF possible alternative strategies for Brazil scenario´s

In this case study it will be evaluated only scenario “A” with 3 possible strategies “SF1’, “SF2” and “SF3” in order to test the method and also as this is a more realistic scenario for the country for the next years, due to the difficulties of having an increase of nuclear energy production in the country due to financial restrictions and also political and public acceptance support.

5.4 Criteria definition and description

Considering the main criteria selected as described on section 4.2.3, the analysis and evaluation process was based on Safety “C1”, Environmental Impact and Waste Management “C2”, Nuclear Security & Nonproliferation “C3”, Economics “C4”, and Country Specific´s “C5”. They are specifically described in table 10 as follows.

Table 10 – Selected Criteria Description

CRITERIA	CODE	DESCRIPTION
Safety	**C1**	Nuclear safety, including Resilience and Reliability of a system/process, ability to tolerate accidents related to operation and transportation. Safety is a critical and very important issue and for Brazilian NPPs it is the priority for the NPPs management team, so it is expected to have a huge weight assumed by the experts during their evaluation.
Environmental Impact & Waste Management	**C2**	Impacts on the environment and management of radioactive waste. A growing concern about the impacts to the future generations to avoid the legacy waste without appropriate disposition and it is critical for Brazil, as to keep growing with nuclear energy generation, the public and neighborhood will request a clear vision for the future and asking for approval of new NPPs sites
Nuclear Security & Nonproliferation	**C3**	Physical protection and safeguards - measures to prevent the proliferation of nuclear weapons and the non-peaceful use of nuclear and radiological materials. Brazil is strongly committed to nonproliferation. Brazil has signed the non-proliferation and has signed an agreement to keep use of nuclear only for peaceful purposes. Since December 1991, all activities within the Brazilian Nuclear Program take place under the safeguards of the International Atomic Energy Agency (IAEA) and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC).
Economics	**C4**	Economic aspects related to operational and maintenance costs, costs related to environmental and socioeconomic impacts. Brazil is very impacted by economics as today the nuclear energy production in the country is only allowed by to state owned companies as Eletronuclear and it is very impacted by cash availability of the govern for new projects and it is always a subject of the country strategy of actual govern.
Country Specific´s	**C5**	Country specific´s criteria - Public acceptance and political support; Technology (availability, suitability, and accessibility); Infrastructure and Long-term Commitment and Development). This is a critical aspect for Brazil as public acceptance is a huge challenge, mainly due to the lack of understanding of the population and due to the constant delays of the country to move forward with the final RW disposal that impacts the overall approval of the nuclear energy. Also, the difficulties with the availability of own technology have strong impact in the strategy decisions.

All the criteria have been evaluated by the experts and it has been questioned if they would add any other criteria to the evaluation of SF management and none have been added by any of them.

5.5 Sub-criteria definition and description

As described in section 4.2.4, Safety (C1) sub-criteria selected are: “System Resilience & Reliability” SC1, “Accident tolerance in Operation” SC2, “Accident tolerance in Transportation” SC3. Environmental & Waste Management (C2) sub-criteria are: “SF and RW inventory impact” SC4, “radiological impact” SC5 and “non-radiological impact” SC6. Nuclear Security & Proliferation Resistance (C3) sub-criteria are: “Physical protection” SC7, “Nuclear nonproliferation & safeguards” SC8 and “Transportation Risk” SC9. Economics (C4) sub-criteria are: “Construction and Operational & Maintenance

(O&M)) Cost” SC10, “Environmental Cost” SC11, and “socioeconomic impacts” SC12. Country Specific´s (C5) sub-criteria are – “Public acceptance and political support” SC13, “Technology Availability/Suitability/Accessibility” SC14, “Infrastructure” SC15, and “Long term commitment and development” SC16. Table 11 describes each sub-criterion.

Table 11 – Selected Sub-criteria Description

SUB-CRITERIA	CODE	DESCRIPTION
System resilience & reliability	**SC1**	Resilience is understood as system's ability to resist an interruption/major problem within safety parameters and to recover within an acceptable time; Reliability that the system will operate as expected for an adequate design time or will operate adequately without failure in a given situation.
Accident tolerance in operation	**SC2**	Ability to offer better resistance during normal operation in accident scenarios
Accident tolerance in Transportation	**SC3**	Ability to offer better performance and tolerance during transport in accident scenarios
SF and RW inventory impact	**SC4**	Impact on the increase in the volume of SF and RW generated
Radiological impact	**SC5**	Assessment of radiological environmental impact for planned exposure situations, and radiological impact on workers and neighboring populations
Non-radiological impact	**SC6**	Non-radiation-related impacts, such as those related to common industrial waste or any other non-radiation-related impacts.
Physical protection	**SC7**	Measures (including structural, technical, and administrative protective measures) taken to prevent an adversary from achieving an undesirable consequence (such as radiological sabotage or the unauthorized removal of nuclear materials or other radioactive materials in use, storage or transport) and to mitigate or minimize o consequences if the adversary initiates such malicious act
Nuclear nonproliferation & safeguards	**SC8**	Measures to prevent the spread of nuclear weapons, promote international cooperation in the peaceful uses of nuclear energy and promote the objective of achieving nuclear disarmament
Transportation risk	**SC9**	Risks related to the security of radioactive materials in transport
Construction and O&M costs	**SC10**	Costs related to construction, manufacturing, operation and maintenance and nuclear licensing
Environmental costs	**SC11**	Costs related to environmental replacement, environmental licensing and financial compensation
Socioeconomic impacts	**SC12**	Defined as impact on culture and customs, language, and demographic characteristics of a community; and changes related to its economic base, main industries, employment patterns & infrastructure
Public acceptance & political support	**SC13**	Public acceptance and political support, with support from neighboring communities, city halls, municipalities, and other interested parties
Technology (availability / suitability / accessibility)	**SC14**	Necessary technology (tools, devices, and techniques) for the solution considering availability, suitability, and accessibility
Infrastructure	**SC15**	Set of services and structures that we need as fundamental conditions for the development and execution of a solution
Long term commitment and development	**SC16**	Long-term commitment to technology development or acquisition

All the sub-criteria have been evaluated by the experts and it has been questioned if they would add any other criteria to the evaluation of SF management and none have been added by any of them.

5.6 Construction of objectives tree considering the criteria, sub-criteria and options of solution

After defining all the criteria and sub-criteria, it is built the AHP criteria x sub-criteria hierarchy tree structure, with the main objective and the pre-selected alternatives for the problem to be solved considering the relationship between the criteria and sub-criteria. Figure 16 shows the Hierarchy Structure tree for Brazil SF strategy decision problem and considering only Angra 1, Angra 2 and Angra 3 scenario (CASE A).

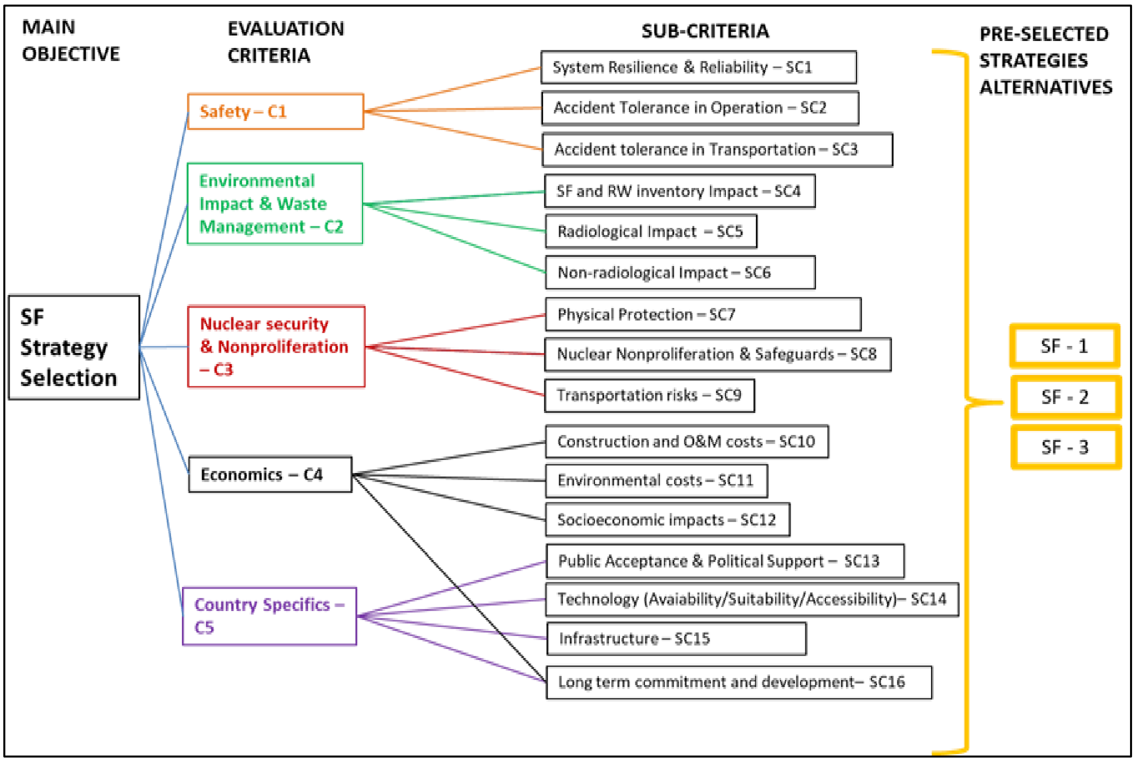


Figure 16 – Hierarchy Structure for SF management strategy for Brazilian case.

5.7 Experts Research and Selection

The expert’s selection has been done considering the stakeholders and possible influencers in the decision-making problem related to SF management. The experts in the SFM area and in criteria and sub-criteria areas are limited and having them available for the research was the first challenge in this study. To start the selection, it has been mapped all the important areas that need to be evaluated considering the criteria C1 to C5 and sub-criteria SC1 to SC16. Also, to have consistency in the opinions, it has been selected preferably high qualified experts, with at least MSc and PhD qualification, and as much as possible more than 10 years of experience, although it has also considered some specific cases with less experience due to specific areas knowledge.

It was considered the leadership position and political relation and power in a decision-making role, in different types of stakeholder's organizations. Public acceptance has also been considered including experts in nuclear and environmental licensing and experts in political roles. Most of the experts have strong international experience, joining frequently International technical meetings (TM), Working Groups (WG) and missions in worldwide recognized organizations as IAEA (International Atomic Energy Agency), WINS (World Institute of Nuclear Security), EPRI (Electric Power Research Institute), WNA (World Nuclear Association), among others, to have the experts updated with international experience and missions (e.g. IAEA OSART mission – Operational Safety Review Team). It has been sent 28 requests for the research, with 18 experts feedback, with the profiles described in table 12.

Table 12 – Experts´ profiles

EXPERT	ACADEMIC QUALIFICATION	OCCUPATION	YEARS OF EXPERIENCE	AREAS OF KNOWLEDGE	INTERNATIONAL EXPERIENCE
1	MSc.	HIGH ADMINISTRATION STAFF & EXPERT	10-20	chemical & nuclear engineering, safety analysis & radiological protection; decommissioning, RW/ SF management & environmental and nuclear licensing	IAEA, WINS, EPRI, WNA TMs (technical Meeting), WG and technical missions and conventions. IAEA expert for OSART Mission
2	Ph.D	HIGH ADMINISTRATION STAFF & EXPERT	30-40	naval & nuclear engineering & nuclear licensing, decommissioning and RW management	IAEA TMs and international missions and conventions. International project development experience
3	Ph.D	EXPERT & MANAGEMENT STAFF	10-20	physicist& nuclear engineering & safety analysis	Participation in international conventions and technical meetings
4	MSc.	EXPERT & MANAGEMENT STAFF	30-40	civil & nuclear engineering & nuclear licensing & radiological protection	IAEA TMs and international missions and conventions. IAEA expert for OSART missions
5	Ph.D	EXPERT & MANAGEMENT STAFF	10-20	civil & nuclear engineering & nuclear licensing, emergency & fire protection planning	IAEA, TMs, WG and international technical missions and conventions.
6	Ph.D	EXPERT & MANAGEMENT STAFF	40-50	it system analysis & nuclear engineering & nuclear licensing and NPP operation expert	IAEA, TMs, WG and international technical missions and conventions.
7	Ph.D	EXPERT	10-20	production, nuclear and geotechnical engineering	
8	Ph.D	EXPERT	40-50	mechanical & nuclear engineering & safety analysis	International experience and publications
9	Ph.D	EXPERT	10-20	eletronic/electrical & nuclear engineering	
10	MSc.	EXPERT AND MANAGEMENT	40-50	mechanical & nuclear engineering & safeguards & nuclear licensing	IAEA, TMs, WG and international technical missions and conventions.
11	MSc.	EXPERT	10-20	mechanical & nuclear engineering & human factor & nuclear licensing	IAEA TMs and technical missions and conventions.
12	MSc.	HIGH ADMINISTRATION STAFF & EXPERT	40-50	mechanical & nuclear engineering	IAEA, EPRI, WANO TMs, WG and technical missions and conventions.
13	Ph.D	EXPERT	20-30	biology & nuclear environmental management & environmental licensing	
14	Ph.D	HIGH ADMINISTRATION STAFF & EXPERT	10-20	eletronic/electrical, nuclear engineering & security expertise & nuclear licensing	IAEA, WINS, TMs, WG and technical missions and conventions.
15	MSc.	EXPERT	10-20	physicist, safeguards & fuel management	IAEA, EPRI TMs, and technical missions and conventions.
16	MSc.	HIGH ADMINISTRATION STAFF & EXPERT	10-20	chemical & nuclear engineering & security expertise	International TMs and conventions.
17	Ph.D	EXPERT	20-30	Physicist & nuclear engineering	
18	Ph.D	EXPERT	10-20	biology & nuclear environmental management & environmental licensing	IAEA, EPRI TMs,and technical missions and conventions and publications

Before starting the research, all the experts were briefed on the subject and it was mentioned that this study had to be considered in a future ‘perspective” as it takes one to two decades to implement such strategy, which is also one of the reasons of this study. The experts’ affiliations are as follows: Eletronuclear - 6 experts; CNEN - 3 experts; National Security Cabinet (GSI) – Presidency of Republic - 2 experts; Brazilian Institute of Nuclear Quality (IBQN) -1 expert; Nuclear area consultants - 2 experts; Brazilian Navy - 4 experts.

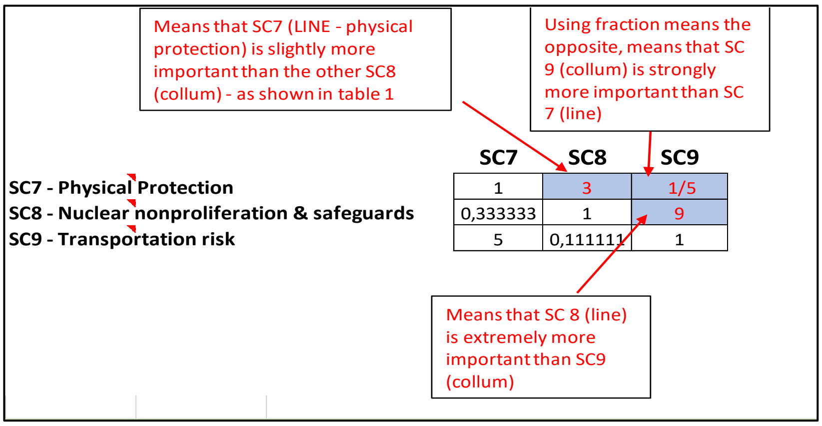
5.8 AHP method calculation

As described in section 3.1.3, it was prepared a spreadsheet with all criteria and sub-criteria as shown left matrix of table 13, where in the first part, the experts insert the weights of each criteria/sub-criteria evaluates in a pairwise comparison to each other. Table 13 shows the example of one reciprocal matrix of the sub-criteria related to “Nuclear Security & Nonproliferation” criteria, where the expert fills the blue cells to express each one comparatively weight. It was built 6 matrices, one for the criterion x criterion pairwise comparison (as example shown in table 14) and 5 more for each sub-criteria to allow pairwise comparisons, as shown in Table 15.

Then, after all the experts’ evaluations, the calculations of the AHP as shown in section 3.1.3, steps 1 until 7 are calculated in other to have the Normalized eigenvector that indicates the relevance of each criteria/sub-criteria evaluated. In the end of the calculations, it is also calculated a consistency ratio (CR) that indicates good consistency when below 10% (0,10).

Table 14 shows an example of the calculation sheet, and it has been replicated for all the criteria and its sub-criteria as shown in table 14 for all sub-criteria evaluations provided by the experts. They all have been combined according to the AHP hierarchy tree and have been synthetized in a table for evaluation, and have been done for each SF scenario strategy, as shown in section 3.1.3. The blue cells are the cells to be filled by the experts considering Saaty´s Fundamental scale.

Table 13 – Reciprocal matrix example of the sub-criteria related to the “Nuclear Security & Nonproliferation” criterion



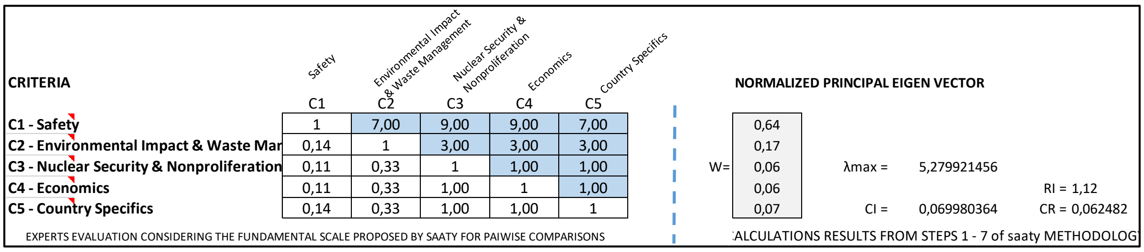
Means that SC7 (LINE - physical protection) is slightly more important than the other SC8 (collum) - as shown in table 1

Using fraction means the opposite, means that SC 9 (collum) is strongly more important than SC 7 (line)

	SC7	SC8	SC9
SC7 - Physical Protection	1	3	1/5
SC8 - Nuclear nonproliferation & safeguards	0,333333	1	9
SC9 - Transportation risk	5	0,111111	1

Means that SC 8 (line) is extremely more important than SC9 (collum)

Table 14 – Case study spreadsheet of experts’ criteria evaluation and AHP calculation example



CRITERIA	Safety C1	Environmental Impact & Waste Management C2	Nuclear Security & Nonproliferation C3	Economics C4	Country Specifics C5
C1 - Safety	1	7,00	9,00	9,00	7,00
C2 - Environmental Impact & Waste Mar	0,14	1	3,00	3,00	3,00
C3 - Nuclear Security & Nonproliferation	0,11	0,33	1	1,00	1,00
C4 - Economics	0,11	0,33	1,00	1	1,00
C5 - Country Specifics	0,14	0,33	1,00	1,00	1

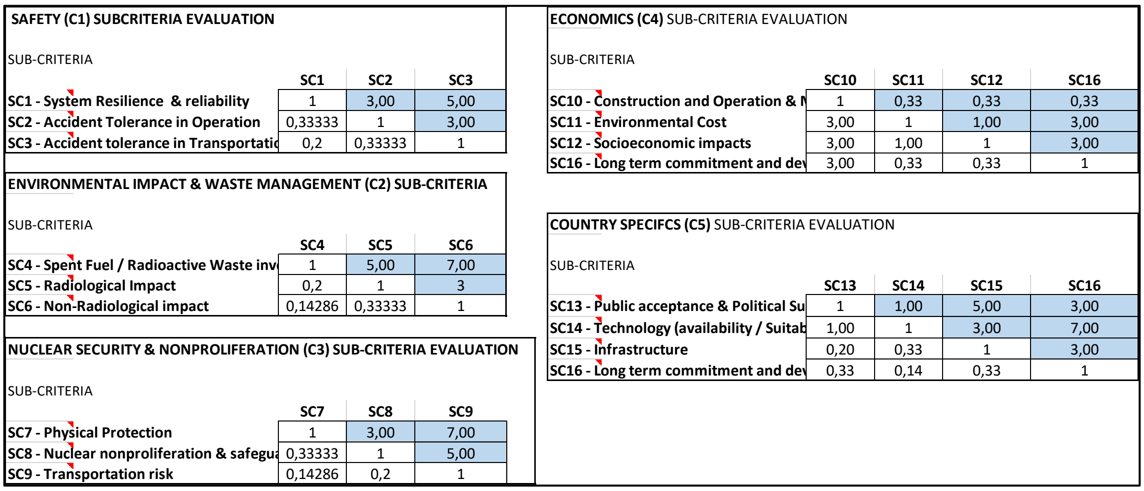
EXPERTS EVALUATION CONSIDERING THE FUNDAMENTAL SCALE PROPOSED BY SAATY FOR PAIWISE COMPARISONS

NORMALIZED PRINCIPAL EIGEN VECTOR

	W				
	0,64				
	0,17				
W=	0,06	λmax =	5,279921456		
	0,06				RI = 1,12
	0,07	CI =	0,069980364		CR = 0,062482

ALCULATIONS RESULTS FROM STEPS 1 - 7 of saaty METHODOLOG

Table 15 – Sub-criteria matrices



SAFETY (C1) SUBCRITERIA EVALUATION

SUB-CRITERIA	SC1	SC2	SC3
SC1 - System Resilience & reliability	1	3,00	5,00
SC2 - Accident Tolerance in Operation	0,33333	1	3,00
SC3 - Accident tolerance in Transportatic	0,2	0,33333	1

ENVIRONMENTAL IMPACT & WASTE MANAGEMENT (C2) SUB-CRITERIA

SUB-CRITERIA	SC4	SC5	SC6
SC4 - Spent Fuel / Radioactive Waste inv	1	5,00	7,00
SC5 - Radiological Impact	0,2	1	3
SC6 - Non-Radiological impact	0,14286	0,33333	1

NUCLEAR SECURITY & NONPROLIFERATION (C3) SUB-CRITERIA EVALUATION

SUB-CRITERIA	SC7	SC8	SC9
SC7 - Physical Protection	1	3,00	7,00
SC8 - Nuclear nonproliferation & safegua	0,33333	1	5,00
SC9 - Transportation risk	0,14286	0,2	1

ECONOMICS (C4) SUB-CRITERIA EVALUATION

SUB-CRITERIA	SC10	SC11	SC12	SC16
SC10 - Construction and Operation & N	1	0,33	0,33	0,33
SC11 - Environmental Cost	3,00	1	1,00	3,00
SC12 - Socioeconomic impacts	3,00	1,00	1	3,00
SC16 - Long term commitment and dev	3,00	0,33	0,33	1

COUNTRY SPECIFCS (C5) SUB-CRITERIA EVALUATION

SUB-CRITERIA	SC13	SC14	SC15	SC16
SC13 - Public acceptance & Political Su	1	1,00	5,00	3,00
SC14 - Technology (availability / Suitab	1,00	1	3,00	7,00
SC15 - Infrastructure	0,20	0,33	1	3,00
SC16 - Long term commitment and dev	0,33	0,14	0,33	1

5.9 Results and Discussion of the AHP method calculations

After the calculation of the AHP based in the experts' evaluations, the data have been consolidated in table 16 with each SF strategy, and all the results used were a average of all the results. It can be clearly seen how heavy the safety weight is in the decision-making process, followed by C2 (Environmental and Waste Management) and C3(Nuclear Security & Nonproliferation) criteria and with less impact the Economics (C4) and country specific´s (C5).

Table 16 – Case study spreadsheet of experts' sub-criteria evaluation and AHP calculation using experts' results average

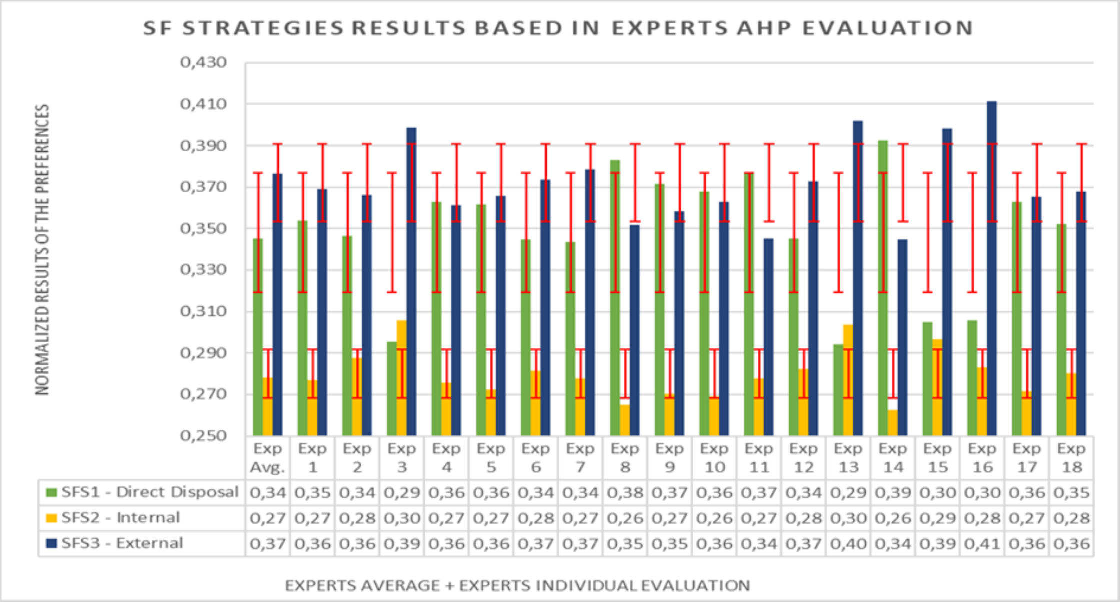
CRITERIA & SUB-CRITERIA	SF1 - Direct Disposal	SF2 – Internal Reprocessing	SF3 – External Reprocessing	CR
SC1 - System Resilience & Reliability	0,13	0,08	0,11	
SC2 – Accident Tolerance in Operation	0,04	0,03	0,04	
SC3 - Accident tolerance in Transportation	0,02	0,02	0,02	
C1 - Safety	0,19	0,13	0,16	0,0502
SC4 - Spent Fuel / Radioactive Waste inventory impact	0,01	0,06	0,09	
SC5 – Radiological Impact	0,03	0,02	0,02	
SC6 - Non-Radiological Impact	0,01	0,01	0,01	
C2 - Environmental Impact & Waste Management	0,05	0,08	0,12	0,0489
SC7 – Physical Protection	0,04	0,02	0,03	
SC8 - Nuclear nonproliferation & safeguards	0,01	0,01	0,01	
SC9 - Transportation risk	0,01	0,01	0,00	
C3 - Nuclear Security & Nonproliferation	0,06	0,04	0,05	0,0548
SC10 - Construction and O&M Costs	0,01	0,01	0,01	
SC11 - Environmental Cost	0,004	0,004	0,006	
SC12 – Socioeconomic impacts	0,004	0,006	0,003	
SC16 - Long term commitment and development	0,002	0,003	0,002	
C4 - Economics	0,02	0,02	0,02	0,0633
SC13 - Public acceptance & Political Support	0,018	0,013	0,023	
SC14 - Technology (availability / Suitability / accessibility)	0,014	0,002	0,012	
SC15 - Infrastructure	0,009	0,005	0,012	
SC16 - Long term commitment and development	0,005	0,006	0,004	
C5 - Country Specific´s	0,03	0,01	0,03	0,0286
TOTAL results	**0,345**	**0,278**	**0,376**	
	2nd option	**3rd option**	**1st option**	

Table 16 shows that the average of the evaluations shows that the most preferable strategy is SF3 (External Reprocessing + Disposal), followed by SF1 (Direct

Disposal) and in as the last one, the SF2 (Internal Reprocessing + Disposal). SF3 and SF1 had very close results, and the main reason most of experts had led to choose SF3 and not SF1, is the benefit of having strong reduction of SF/RW that SF3. It was found that the experts prefer to reduce the volume of SF and prefer to keep HLW in a reduced volume, then keeping SF storage for future use, as the preferred option was SF3. Also, this is due to the high costs to keep SF in storage, which includes equipment costs, casks costs and O&M costs. It was found that the reason of the experts did not choose SF2 as second option due to the risk to not succeed in technology development of the reprocessing process, due to safeguards concerns and, also, as the reprocessed fuel would have to be used in another type of plant what would also make it more difficult to be used. Also, it has been verified if all the CRs are below 10% to confirm the consistency evaluation.

In Figure 17, to have the visual of all experts results together, it has been built a graphic with all the experts results combined, with the standard deviation bar of the values.

Figure 17 – SF strategies ranking based on experts' evaluation with standard deviation bar.



	Exp Avg.	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Exp 10	Exp 11	Exp 12	Exp 13	Exp 14	Exp 15	Exp 16	Exp 17	Exp 18
🟩 SFS1 - Direct Disposal	0,34	0,35	0,34	0,29	0,36	0,36	0,34	0,34	0,38	0,37	0,36	0,37	0,34	0,29	0,39	0,30	0,30	0,36	0,35
🟨 SFS2 - Internal	0,27	0,27	0,28	0,30	0,27	0,27	0,28	0,27	0,26	0,27	0,26	0,27	0,28	0,30	0,26	0,29	0,28	0,27	0,28
🟦 SFS3 - External	0,37	0,36	0,36	0,39	0,36	0,36	0,37	0,37	0,35	0,35	0,36	0,34	0,37	0,40	0,34	0,39	0,41	0,36	0,36

Analyzing the average results of Figure 17, it shows clearly that SF2, is not even close to SF1 and SF3, besides they are close, the average shows that SF3 deviation is higher than SF1, and 12 of the experts have chosen SF3 and none have chosen SF2. Also, it´s realized that 4 Experts (4, 5, 10 and 17) have almost given the same results for both SF1 and SF3, 2 slightly preferring SF1 and 2 preferring SF3. Experts 8, 9, 11 and

14 have preferred SF1, due to safety and transport concerns, which is their main expertise area. Experts 4 and 10 have almost given the same almost the same results between SF1 and 3, slightly preferring SF1. These results can be also attributed to the safeguards concern of Experts 10 and 14, and Experts 4, 8, 11, and 17 that have visualized some difficulties in transport of SF and all reprocessing process, as they come from radiological protection, safety analysis and nuclear fuel design area.

Figure 17 shows concludes that most preferred strategy is SFS3 (12) with 66,7%. The second preferred is SFS1 with (6) 33,3%. No expert has chosen SFS2, which is something predictable due to all difficulties of developing such technology and due the lack of SF production to make it profitable. Experts average has also chosen SFS3, ratifying the overall opinion.

After the calculation of the AHP, the results indicate a massive preference of SFS3, followed by SFS1, due to the importance of reducing volume of RW and SF in the process, as the inventory of each one directly impacts the costs and the environment. SF1 could also be a possibility, due if sending SF for reprocessing outside of the country not being achievable due to difficulties in agreements between the company and the countries related; SFS2 has not been considered by none of the experts, and it is understandable due to the high risk of not being able to develop the reprocessing technology, due to safeguards and safety concerns and the unplanned costs it could generate.

The methodology application to the Brazil case can be considered highly congruent as the final average result have coincided with the more experienced experts in the area, which are Experts 1, 2, 6 and 12, selecting SF3. Also, it was clearly that safety assessment and safeguards experts would prefer SF1, as it has less safety risks and safeguards concerns. So, the results were consistency with what was expected and confirmed by the Consistency Rations that were below 10% confirming it.

5.10 Cost estimate of the main solution alternatives

The objective of this section is to evaluate the cost estimative of each alternative selected, considering Brazil country characteristics.

Raoni Jonusan [JONUSAN, 2021] has estimated the cost of OFC and CFC for Brazilian nuclear energy production scenarios, using the OECD/NEA guide “The Economics of the Back End of the Nuclear Fuel Cycle” [OECD/NEA, 2013], IAEA [2020], and other international references, assuming Angra 1, Angra 2 and Angra 3 in operation and, with the increased nuclear generation predicted in PNE20250 [EPE, 2020] and it´s SF generation, employing OECD/NEA method. It has been considered the investment and O&M costs. Raoni has not inserted the external reprocessing cost calculation, as he has not initially identified it as a possibility, but in the conclusions, he mentions that it could be the more attractive solution and it should be considered. Appendix D shows the calculations performed by Raoni in his study.

Table 17 shows the mean values calculated by Raoni considering the “pessimist” estimative, “reference” estimative and the “optimist” estimative as shown in Appendix D.

Table 17 – Cost estimation of the Brazilian nuclear fuel cycle back-end by installation in $2019 Million adapted from [JONUSAN, 2021]

Facility Cost estimative (US$ million)	**Angra 1 + Angra 2 + Angra 3**	
	OFC	**CFC**
Interim Storage Facility Oversight investment	737,35	783,39
Interim storage facility: O&M	15,85	16,23
Integrated reprocessing plant: Overnight investment	-	7.151,94
Integrated reprocessing plant: O&M	-	506,37
SNF encapsulation plant: Overnight investment	249,93	295,37
SNF encapsulation plant: O&M	24,75	27,63
Geological repository: Overnight investment	3.295,20	3.751,95
Geological repository: O&M	102,11	102,08
Geological repository: Closure	706,20	706,20
Transport	0,08	0,08
Total	**5.131,47**	**13.341,23**

In his study he estimates that Angra 1, 2 and 3 would have a cost estimate around US$5,131 billion for OFC and a CFC (with internal reprocessing) costing around US$13.341 billion of dollars. The CFC has been calculated as 2.5 to 3.0 times more than the OFC. In Rauni’s study he has not calculated the cost for external reprocessing, but Rauni’s study raises that having external country partners to reprocess the SF could be a good solution, although he had no cost estimation for such activity of having the SF externally reprocessed.

Estimating the value for external reprocessing is very difficult, as there are no values in international references as the negotiations are between companies and the data are confidential. To calculate an estimative of this cost, the following assumptions have been considered:

- Cost of US$1.000/KgHM [EPRI, 2023; NEA, 2013] for SF reprocessing
- Addiction of 48% of taxes for international services in Brazil
- 12% of profit, according to "*Tribunal de Contas da União*" recommendation [TCU 1; 2014]
- Transport estimation of 10%
- Prediction of 2095 SF for Angra 1, 2873 SF for Angra 2 and 2845 SF for Angra 3 [ELETRONUCLEAR, 2019]
- Each Angra 1 SF has 0,359 tHM [ELETRONUCLEAR, 2024]
- Each Angra 2 and 3 SF has 0,514 tHM [ELETRONUCLEAR, 2024]
- To keep the calculation conservative, no reduction in the cost have been added due to the energy that have been produced after the reprocessing process during the new reprocessed fuel use. This value attributed to the energy in each SF, could be very valuable in the final cost estimative, during negotiations phase.

Table 18 shows an estimative calculation of the reprocessing cost considered the previous mentioned assumptions. The total value of this calculation is very conservative, as it does not consider the value of the remaining spent fuel radionuclides energy, that could reduce considerably the total cost of external reprocessing, if they are valued during the negotiations for external reprocessing.

Table 18 – External Reprocessing Cost Estimate

<table>
<tr><th colspan="8">External Reprocessing Cost Estimate</th></tr>
<tr><th>NPP</th><th>tHM</th><th>Qty of SF produced</th><th>US$/kgHM [EPRI, 2023; NEA, 2013]</th><th>Brazilian taxes</th><th>Profit</th><th>Transport</th><th>Total</th></tr>
<tr><td>Angra 1</td><td>0,36</td><td>2095</td><td>$ 1.000.000</td><td>48%</td><td>12%</td><td>10%</td><td>$ 1.371.358.173</td></tr>
<tr><td>Angra 2</td><td>0,51</td><td>2873</td><td>$ 1.000.000</td><td>48%</td><td>12%</td><td>10%</td><td>$ 2.692.595.826</td></tr>
<tr><td>Angra 3</td><td>0,51</td><td>2845</td><td>$ 1.000.000</td><td>48%</td><td>12%</td><td>10%</td><td>$ 2.666.354.029</td></tr>
<tr><td colspan="2">Total</td><td>7813</td><td colspan="2"></td><td colspan="2">Total</td><td>$ 6.730.308.028</td></tr>
</table>

Table 19 shows the summary results of the cost estimates and AHP calculation.

Table 19 – Summary Results Table

Summary Results table			
	SF1 - Direct Disposal	SF2 – Internal Reprocessing	SF3 – External Reprocessing
AHP evaluation	0,345	0,278	0,376
	2nd	3rd	1st
Cost estimative (US$Milion)	5.131,50	13.341,00	6.730,3
	1st	3rd	2nd

It could not be found an estimative of SF reprocessing outside of the country as it is a specific negotiation between countries and companies and no reference was found, so the cost evaluation has been complemented with an estimative of the costs of external reprocessing (as table 18), probably its costs will be lower than the calculated in table 18, because it has not considered that the SF have energy inside that could possibly be discounted of the reprocessing cost. SF 1, SF2 and SF 3 have been compared in table 19, where SF1, has previously became with less cost than SF3 and SF2.

As shown in section 5.9, AHP evaluation has chosen the SF3 strategy, but in the cost estimate, SF3 had a cost estimate around 20% higher than SF1, but it was not considered the energy value of the SF for the reprocessing NPPs in the SF3 calculation. Considering the SF3 probably will have a strong reduction of cost, it has a very high possibility of being also more cost effective between all the scenarios strategies. SF3 also has a very positive advantage of the possibility of being reprocessed by batches, spreading the investment, and the fact of reducing the RW volume will also be very useful in case of having the final disposal for HLW delayed. SF2 has the last result of the 3 options, as it was expected due to all the difficulties related to technology, safeguards and all risks involved.

SF1 and SF3 became very close in both AHP and Cost evaluation, and both could be a possible solution, and a more detailed cost calculation could be made, to have a more accurate value for SF3, that could only be made having an official proposal by one of the companies that have this technology.

Considering the AHP results, and the high possibility of a reduction of the cost estimate of SF3, this would be the preferred option, followed by SF1. SF2, with internal reprocessing would be the last option, due to the higher cost of the reprocessing technology and all the difficulties related to this option, that have been revealed in the results of the AHP evaluation.

6. Conclusions

The main objective of this study has been achieved, proposing a methodology, based on MCDM analysis, to indicate the preferred strategy for SF management decision-making problem, passing through the MCDM method selection, experts' selection, criteria, and sub-criteria definition and description, based on international experience and the application in Brazil scenario, which motivated this thesis. The methodology proposed has been validated by the experts with a real practical example in Brazil scenario. Experts were asked to suggest other criteria or sub-criteria, but one has added any, confirming the comprehensive research that was performed.

This thesis has reached to the following main contributions and relevant results:

1. It was summarized the SF and HLW Management worldwide, as well as the specificities of the Brazil´s current scenario.

2. There were compared the main MCDM methods considering their advantages and disadvantages, concluding that AHP is one of the most recommended for SF and HLW management decision-making support.

3. It has been proposed a methodology to evaluate different options of SF and HLW management scenarios, based on AHP and international benchmark research.

4. As part of the methodology, it has been established the main criteria and sub-criteria to be evaluated, being ratified by the experts during the research, as shown in section 4.2.3 and 4.2.4. The criteria recommended are: Safety "C1", Environmental Impact and Waste Management "C2", Nuclear Security & Nonproliferation "C3", Economics "C4", and Country Specifics "C5".

5. It has been researched the experts' selection practice. It was found that, despite the widespread recognition of its importance for the AHP process, there are multiple approaches with almost no common requirements. Then this thesis recommends a maximum of 30 evaluations, as significance of expert competence consideration is inversely proportional to the expert group size. It is also recommended to have the relevant number of stakeholders involved, with experience background (with 10

years or more), preferably with MSc or PhD degree, or working as decision-making person and with knowledge in the criteria and sub-criteria selected.

6. The proposed methodology has been applied to the Brazil´s case. The application showed a significant practical value, demonstrating its capacity for the assessment of many different scenarios and alternatives. There were identified, described, evaluated and ranked, the main Brazil SF Management options SF1, SF2 and SF3, as described in section 5. Consistent and valid results were achieved, integrating the experience of multiple expert´s in several areas, with international background in the criteria and sub-criteria proposed. The results provide a standard deviation for each SF strategy.

7. To complement the AHP method calculation, it was performed an estimative of cost of SF1, SF2 and SF3, including an estimative of the external reprocessing costs. Although no detailed information was found about the costs involved in external reprocessing, this is probably an economical option as it will reduce more than 80 % of the SF volume, and consequentially the costs of SF storage, providing a reduction of nuclear legacy for future generations.

After the expert’s evaluation, SF3 (External Reprocessing + Disposal) was selected as the preferred option, followed by SF1 (Direct Disposal), more conservative, but none has chosen SF2 (Internal Reprocessing + Disposal). The results were predicted, as SF1, with internal reprocessing has many challenges related to technology, safeguards issues, scale, etc. that makes it the most difficult strategy to be implemented. In section 5.10, a cost evaluation has been accomplished for SF1, SF2 and SF3. SF1 had the lower cost, followed by SF3 and SF2. Integrating the expert´s evaluation through the AHP process with the cost evaluation, SF1 and SF3 have very similar results, but there could be an advantage of SF3, if the remaining energy inside the SF could be discounted from the reprocessing costs.

The methodology application to the Brazil case can be considered highly congruent as the final average result have coincided with the more experienced experts in the area, which are Experts 1, 2, 6 and 12, selecting SF3. Also, it was clearly that safety assessment and safeguards experts would prefer SF1, as it has less safety risks and safeguards concerns. So, the results were consistency with what was expected and confirmed by the Consistency Rations that were below 10% confirming it.

If Brazil moves forward to its planning of having 8 more NPPs in the following years, SF2 may be a little more compensating due to the scale, but it is not expected that be better than having SF external reprocessed with an existing reprocessing plant. This would demand a government agreement with another one with reprocessing technology and should have higher safeguards measures to keep nuclear material safe and avoid security risks.

This thesis also proposes the following complementing research and recommendations: 1) To perform a more detailed cost estimation, with a proposal for the having SF externally reprocessed, using the methodology of [RODRÍGUEZ-PENALONGA and MORATILLA-SORIA, 2019] and [JONUSAN, 2021]; 2) To perform a qualitative analysis combined with the AHP evaluation to detail the evaluation as proposed by IAEA with specific key indicators and EPRI with Figure of Merits (FOM), to increase the accuracy of the methodology; 3) To complement the methodology including scenarios SF4, SF5, SF6 and SF7. Considering that these scenarios there is an increase of scale that could lead to a better cost-benefit of the reprocessing process in the decision-making process.4) That the assessment in chapter 5 and all the calculation be reviewed and revised from 5 to 5 years, to incorporate the scenarios and assumptions modifications changes through time.

References

ANDRIANOV A.A., ANDRIANOVA O.N., KUPTSOV I.S., SVETLICHNY L.I., UTIANSKAYA T.V., **Multi-criteria Comparative Evaluation of Nuclear Energy Deployment Scenarios with Thermal and Fast Reactors**, Journal of nuclear Fuel Cycle and Waste Technology. Daejeon, Korea. 2019. Available at <https://doi.org/10.7733/jnfcwt.2019.17.1.47>. Accessed April 5th, 2022.

BHUSHAN N. AND RAI K., **Strategic Decision Making - Applying the Analytic Hierarchy Process**. 2004. Available at <Strategic Decision Making: Applying the Analytic Hierarchy Process | SpringerLink>. Accessed in February 19th 2023.

BILAL A.A., MAMLOOK R., MOHSEN M.S., **Multi-criteria selection of electric power plants using analytical hierarchy process, 1999**. ScienceDirect - Elsevier B.V.. Available at <https://doi.org/10.1016/S0378-7796(99)00004-8>. Accessed June 6th, 2022.

BRANS, J.P., MARESCHAL, B., FIGUEIRA, J.R., GRECO S., EHROGOTT M, **Multiple Criteria Decision Analysis: State of the Art Surveys**, chapter 5, Promethee Methods, ResearchGate. 2005. Available at <https://www.researchgate.net/publication/226334105_Promethee_Methods>. Accessed October 21st, 2022.

BRASIL, Lei nº 10.308/2001. **Regulates on Site Selection, Construction, Licensing, Operation, Surveillance, Costs, Reparations, Liabilities and Warranties regarding Radioactive Waste Deposits** (in Portuguese). Diário Oficial da União, Poder Executivo, Brasília, DF, November 21st, 2001.

CBO, **Costs of Reprocessing Versus Directly Disposing of Spent Nuclear Fuel - Statement of Peter R. Orszag**. Washington, USA. 2007. Available at <https://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/88xx/doc8808/11-14-nuclearfuel.pdf>. Accessed October 21st, 2022.

CDTN, Centro Tecnológico Nuclear e Ambiental – CENTENA. Available at <https://www.gov.br/cdtn/pt-br/projetos-especiais/centena>. Accessed April 07th 2023.

CNEN, **Management of Financial Resources for the Decommissioning of Nuclear Power Plants** (in Portuguese). CNEN NN 9.02. 2016. Rio de Janeiro, Brazil. Available at <http://appasp.cnen.gov.br/seguranca/normas/pdf/Nrm902.pdf>. Accessed October 21st, 2022

CNEN, **National report of Brazil 2017 for the 6th review meeting of the joint convention on the safety of spent fuel management and on the safety of radioactive waste management**. Rio de Janeiro, Brazil. 2017. Availableat<http://antigo.cnen.gov.br/images/cnen/documentos/drs/relatorios-de-convencao/National-Report-of-Brazil-2017.pdf>. Accessed July 3rd, 2020.

CNEN, **Nuclear Power Plants Decommissioning** (in Portuguese), CNEN NN 9.01. Brazil.2012. Available at <http://appasp.cnen.gov.br/seguranca/normas/pdf/Nrm901.pdf>. Accessed October 21st, 2022

CNEN, **Nuclear Safety Glossary** (in Portuguese), Rio de Janeiro, Brazil. 2020. Available at <http://appasp.cnen.gov.br/seguranca/normas/pdf/glossario.pdf>. Accessed October 21st, 2022.

CNN Brasil, **Technical Report of Angra 3 will be presented until end of the year** (in Portuguese). 2022. Available at <https://www.cnnbrasil.com.br/business/2021/07/03/relatorio-tecnico-sobre-angra-3-deve-ser-apresentado-ate-o-final-deste-ano>. Accessed October 20th, 2021.

DEAN M., **A Practical Guide to Multi-Criteria Analysis**. 2022. DOI:10.13140/RG.2.2.15007.02722. University College London.

DOE, **Fuel Cycle Potential Waste Inventory for Disposition**. Washington, USA. 2012. Available at <https://www.energy.gov/sites/default/files/2013/06/f1/FY12%20Fuel%20Cycle%20Potential%20Waste%20Inventory%20for%20Disposition%20Rev%205.pdf>. Accessed October 25th, 2022.

DOE, **High-Level Waste**. Washington, USA. 2020. Available at <https://www.directives.doe.gov/terms_definitions/high-level-waste>. Accessed October 25th, 2022.

DOE, **Spent Fuel and Waste Disposition**. Washington, USA. 2020. Available at <https://www.energy.gov/ne/spent-fuel-and-waste-disposition>. Accessed October 22nd 2022.

DYASI P.B., **Application of the analytic hierarchy process in selecting medium-term storage options for spent nuclear fuel in South Africa**. Master of Engineering in Nuclear Engineering at the North-West University, South Africa. 2021. Available at <https://repository.nwu.ac.za/handle/10394/37659. Accessed October 21st, 2022

EASAC, **Management of spent nuclear fuel and its waste**. European Commission Joint Research Centre, Brussels, Belgium. 2014. Available at <https://www.interacademies.org/sites/default/files/publication/full_report_spent_nuclear_fuel_webvs.pdf>. Accessed October 15th, 2022.

ELETRONUCLEAR S.A., **Angra 3 tem licença de instalação renovada pelo IBAMA.** Rio de Janeiro, Brazil. 2022. Availableathttps://www.eletronuclear.gov.br/Imprensa-e-Midias/Paginas/Angra-3-tem-licen%C3%A7a-de-instala%C3%A7%C3%A3o-renovada-pelo-Ibama.aspx. Accessed October 21st, 2022.

ELETRONUCLEAR S.A., BOURCHEID, **Relatório Ambiental Simplificado (RAS) da Unidade de Armazenamento Complementar a Seco de Combustível Irradiado da CNAAA**. Brasil. 2019. Available at <https://www.eletronuclear.gov.br/Sociedade-e-Meio-Ambiente/Documents/Licenciamento%20Ambiental/Relat%C3%B3rio_Ambiental_Simplificado.pdf>. Accessed November 2nd 2022.

ELETRONUCLEAR S.A., **Eletronuclear solicita à CNEN extensão de vida útil de Angra 1**. Brazil. 2019. Available at <https://www.eletronuclear.gov.br/Imprensa-e-Midias/Paginas/Eletronuclear-solicita-%C3%A0-CNEN-extens%C3%A3o-de-vida-%C3%BAtil-de-Angra-1.aspx>. Accessed November 2nd, 2022.

ELETRONUCLEAR S.A., **Gerenciamento de Resíduos**. Brazil. 2021. Available at <https://www.eletronuclear.gov.br/Sociedade-e-Meio-Ambiente/Paginas/Gerenciamento-de-residuos.aspx>. Accessed January 10th, 2022,

ELETRONUCLEAR S.A., **Nossas Atividades**. Brazil. 2022. Available at <https://www.eletronuclear.gov.br/Nossas-Atividades/Paginas/default.aspx>. Accessed January 10th, 2022.

ELETRONUCLEAR S.A., **Policy for Safely Management of RW and SF from Central Nuclear Almirante Alvaro Alberto**. Brazil, 2017. Available at <https://www.eletronuclear.gov.br/Documents/politicas-empresariais/POL%C3%8DTICA%20PARA%20O%20GEERENCIAMENTO%20SEGURO%20DE%20RES%C3%8DDUOS%20RADIOATIVOS%20E%20COMBUST%C3%8DVEL%20CENTRAL%20NUCLEAR.pdf>. Accessed November 1st 2022.

ELETRONUCLEAR S.A., **Preliminary Decommissioning Plano resume of CNAAA site focused in the Spent Fuel Dry Storage of CNAAA + CNAAA Preliminary Decommissioning Plan**. Rio de Janeiro, Brazil. Available at<http://licenciamento.ibama.gov.br/Nuclear/CNAAA%20-%20Central%20Nuclear%20Almirante%20Alvaro%20Alberto/Eletronuclear%20-%20CNAAA%20-%20Unidade%20de%20Armazamento%20a%20Seco/Processo%2002001.0075992018-65%20-%20Unidade%20de%20Armazenamento%20a%20Seco%20-%20CNAAA/%5B221%5D-5191125_Anexo_ALI.T_066_2019.pdf>.Accessed November 2nd, 2022.

ELETRONUCLEAR, **Top ten goals**. 2020. Available at <https://www.eletronuclear.gov.br/Quem-Somos/Governanca/Documents/Top%20Ten%20da%20Eletronuclear.pdf>. Accessed in January 15th 2023.

EPE, PNE 2050 – **Plano Nacional de Energia, Ministério de Minas e Energia**. Rio de Janeiro, Brazil. 2020. Available at <https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-563/Relatorio%20Final%20do%20PNE%202050.pdf>. Accessed in October 21st, 2022.

EPRI, **Decision Framework for Evaluating Advanced Nuclear Fuel Cycle Options**, California, USA. 2011. Available at <https://www.epri.com/research/products/1022912>. Accessed October 19th, 2020.

EPRI, **Nuclear Fuel Cycle Cost Comparison Between Once-Through and Plutonium Single-Recycling in Pressurized Water Reactors**, California, USA. 2009. Available at <https://www.epri.com/research/products/1018575>. Accessed in April 19th, 2024.

EPRI, **Nuclear Fuel Reprocessing: for the Advanced Nuclear Era**, California, USA. 2023. Available at <https://www.epri.com/research/programs/065093/results/3002026537>. Accessed in April 19th, 2024.

EPRI, **Program on Technology Innovation: Summary of 2014 EPRI Nuclear Fuel Cycle Assessment Workshop – Day 1: Trial Implementation of EPRI Decision Framework.**2014. Available at <https://www.epri.com/research/products/000000003002002784> Accessed in 22th April of 2023.

EURATOM, **Report of the European Atomic Energy Community on the implementation of the obligations under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management**, Vienna, Austria. 2015. Available at https://energy.ec.europa.eu/system/files/2014-10/201505_fifth_review_meeting_of_contracting_parties_0.pdf>. Accessed October, 21st, 2022,

FIGUEIRA J.R., GRECO S., ROY B., SLOWINSKI R., **Handbook of Multicriteria Analysis – ELECTRE Methods: Main Features and Recent Developments**, Springer-

Verlag Berlin Heidelberg. 2010. Available at <https://www.jstor.org/stable/41494956>. Accessed October 21st, 2022.

GAO R., NAM H.O., KO W. II, JANG H., **National options for a sustainable nuclear energy system: MCDM evaluation using an improved integrated weighting approach**. Korea Atomic Energy Research Institute, Daejeon, Korea. 2017. Available at <https://www.mdpi.com/1996-1073/10/12/2017>. Accessed in October 21st, 2022.

GRECO S., EHRGOTT M., FIGUEIRA J.R., **Multiple Criteria Decision Analysis - State of the Art Surveys**. Springer New York, New York, USA. 2016. Available at <https://doi.org/10.1007/978-1-4939-3094-4>. Accessed October 21st, 2022.

HAFEZALKOTOB A., HAFEZALKOTOB A., LIAO H., HERRERA F., **An overview of MULTIMOORA for multi-criteria decision-making: Theory, developments, applications, and challenges**. ScienceDirect - Elsevier B.V. 2019. Available at <https://doi.org/10.1016/j.inffus.2018.12.002>. Accessed October 21st, 2022.

HOLTEC INTERNATIONAL, **HI-STORE CISF (Consolidated Interim Storage Facility).** 2021. Available at <https://holtecinternational.com/products-and-services/hi-store-cis/> Accessed October 8th, 2021.

IAEA 1, **Spent fuel management options**. Vienna, Austria. 2021. Available at <https://www.iaea.org/topics/spent-fuel-management>. Accessed March 23rd, 2021.

IAEA, **Application of MCDA Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the Inpro Collaborative Project Kind**. Nuclear Energy Series, NG-T-3.20, Vienna, Austria. 2019. Available at <https://www.iaea.org/publications/12373/application-of-multi-criteria-decision-analysis-methods-to-comparative-evaluation-of-nuclear-energy-system-options-final-report-of-the-inpro-collaborative-project-kind>. Accessed October 21st, 2022

IAEA, **Application of the Concepts of Exclusion, Exemption and Clearance**, IAEA Safety Standards Series No. RS-G-1.7. Vienna, Austria. 2004. Available at <https://www.iaea.org/publications/7118/application-of-the-concepts-of-exclusion-exemption-and-clearance<. Accessed October, 21st, 2022.

IAEA, **Classification of Radioactive Waste**. Generic Safety Guide Nº GSG-1. Vienna, Austria. 2009. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf>. Accessed October, 21st, 2022.

IAEA, **Costing Methods and Funding Schemes For Radioactive Waste Disposal Programs**. Nuclear Energy Series No. NW-T-1.25. Vienna, Austria. 2020. Available at <https://www.iaea.org/publications/13508/costing-methods-and-funding-schemes-for-radioactive-waste-disposal-programmes>. Accessed October 21st, 2022.

IAEA, **Decommissioning of Facilities**. General Safety Requirements Nº. GSR Part 6, Vienna, Austria. 2014. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/Pub1652web-83896570.pdf>. Accessed October 21st, 2022.

IAEA, **Decommissioning of Nuclear Power Plants, Research Reactors, and Other Nuclear Fuel Cycle Facilities**, Specific Safety Guide No. SSG-47, Vienna, Austria. 20 14. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/P1812_web.pdf>. Accessed October 21st, 2022

IAEA, **Decommissioning Strategies for Facilities Using Radioactive Material**. Safety Report Series No 50, Vienna, Austria. 2007. Available at <https://www.iaea.org/publications/7540/decommissioning-strategies-for-facilities-using-radioactive-material>. Accessed October 21st, 2022.

IAEA, **Disposal of Radioactive Waste**. Safety Standards Series No. SSR-5. Vienna, Austria. 2011. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/Pub1449_web.pdf>. Accessed October 26th, 2022.

IAEA, **Energy, Electricity and Nuclear Power Estimates for the Period up to 2050**. Reference DATA Series Nº 1. Vienna, Austria. 2022. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-42_web.pdf>. Accessed October 21st, 2022.

IAEA, **France's Efficiency in the Nuclear Fuel Cycle: What Can 'Oui' Learn?.** 2019. Available at <https://www.iaea.org/newscenter/news/frances-efficiency-in-the-nuclear-fuel-cycle-what-can-oui-learn>. Accessed in April 08th 2023.

IAEA, **Geological Disposal Facilities for Radioactive Waste**, Specific Safety Guide, SSG-14. Vienna, Austria. 2011. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1483_web.pdf. Accessed October 21st, 2022.

IAEA, **Interim Storage of Radioactive Waste Packages. Technical Report Series 390 – TRS 390**. 1998. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/TRS390_scr.pdf>. Accessed April 08th 2023.

IAEA, **International Safeguards in the Design of Facilities for Long Term Spent Fuel Management**. Nuclear Energy Series, NF-T-3.1. Vienna, Austria. 2018. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1767_web.pdfhttps://www-pub.iaea.org/MTCD/publications/PDF/Pub1368_web.pdf>. Accessed January 15th 2023.

IAEA, **Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management**. Vienna, Austria. 2022. Available at <https://www.iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste>. Accessed in October 13th 2022

IAEA, **Management of Spent Fuel from Nuclear Power Reactors Learning from the Past, Enabling the Future, Proceedings of an International Conference**, Vienna, Austria. 2019. Available at <https://www.iaea.org/publications/14680/management-of-spent-fuel-from-nuclear-power-reactors>. Accessed October 21st, 2022.

IAEA, **Occupational Radiation Protection**. General Safety Guide No GSG-7. Vienna, Austria. 2018. Available at <https://www-pub.iaea.org/mtcd/publications/pdf/pub1785_web.pdf>. Accessed October 27th, 2022.

IAEA, **Policies and strategies for radioactive waste management**. Nuclear Energy Series, NW-G-1.1. Vienna, Austria. 2022. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1396_web.pdfhttps://www-pub.iaea.org/MTCD/publications/PDF/Pub1368_web.pdf>. Accessed January 15th 2023.

IAEA, **Predisposal Management of Radioactive Waste from Nuclear Power Plants and Research Reactors**. Specific Safety Guide Nº. SSG-40, Vienna, Austria. 2016. Available at <https://www.iaea.org/publications/10923/predisposal-management-of-radioactive-waste-from-nuclear-power-plants-and-research-reactors>. Accessed October 21st, 2022.

IAEA, **Predisposal Management of Radioactive Waste**. General Safety Requirements Part 5 – GSR part 5, Vienna, Austria. 2009. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/Pub1368_web.pdf>.Accessed October 21st, 2022.

IAEA, **Protection against internal and external hazards in the operation of nuclear power plants**. Specifc Safety Guide, SSG-77. Vienna, Austria. 2022. Available at <https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1991_web.pdfhttps://www-pub.iaea.org/MTCD/publications/PDF/Pub1368_web.pdf>. Accessed January 15th 2023.

IAEA, **Safety Glossary – Terminology Used in nuclear Safety and Radiation protection 2018 Edition**. Vienna, Austria. 2018. Available at <https://www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf>. Accessed October 21st, 2022.

IAEA, **Status and trends in spent fuel and radioactive waste management**, Nuclear Energy Series Nº NW-T-1.14, Vienna, Austria. 2022. Available at <https://www.iaea.org/publications/14739/status-and-trends-in-spent-fuel-and-radioactive-waste-management>. Accessed October 21st, 2022.

IAEA, **Storage of Spent Nuclear Fuel**, Specific Safety Guide, SSG-15, Vienna, Austria. 2020. Available at <https://www.iaea.org/publications/13516/storage-of-spent-nuclear-fuel>. Accessed October 21st, 2022.

IAEA, **The importance of safe, secure and sustainable spent fuel management**, Vienna, Austria. 2019. Available at <https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull60-2/6020101.pdf>. Accessed October 21st, 2022.

IBAMA, **Installation License nº 291/2009 of Angra 3** (in Portuguese). Rio de Janeiro, Brazil. 2009. Availableat<https://servicos.ibama.gov.br/licenciamento/consulta_empreendimentos.php>. Accessed October 21st, 2022.

IBAMA, **Previous License nº 279/2008 of Angra 3** (in Portuguese). 2008. Available at <https://servicos.ibama.gov.br/licenciamento/consulta_empreendimentos.php>. Accessed October 20th, 2022.

JATO-ESPINO D.1, MARTÍN-RODRÍGUEZ A., MARTÍNEZ-CORRAL A. and SAÑUDO-FONTANEDA L.A., **Multi-expert multi-criteria decision analysis model to support the conservation of paramount elements in industrial facilities**. 2022. Available at <https://doi.org/10.1186/s40494-022-00712-7>. Accessed in February 22nd 2023

JIMÉNEZ-MARTÍN A., MATEOS A. AND SABIO P., **Dominance Measuring Methods within MAVT/MAUT with Imprecise Information concerning Decision-Makers' Preferences**. ETSI Informáticos, Universidad Politécnica de Madrid. Spain. 2014.

JONUSAN, R.A.S., **Analysis of the disposal of spent nuclear fuel in Brazil**, Minas Gerais Federal University, Minas Gerais, Brazil. 2021. Available at <https://repositorio.ufmg.br/bitstream/1843/41268/1/Tese_Raoni_Ad%C3%A3o%28A%29.pdf>. Accessed October 21st, 2022.

KIM S., KIM J. AND CHO D., **Comparative Evaluation of Direct Disposal and Pyro-SFR Nuclear Fuel Cycle Alternatives Using Multi Criteria Decision Making in Korea**,

Korea Atomic Energy Research Institute, Daejeon, Korea. 2021. Available at <https://www.mdpi.com/1996-1073/14/12/3590>. Accessed October 21st, 2022.

KUMAR A., SAH B., SINGH A.R., DENG Y. , HE X. , KUMAR P., BANSAL R.C., **A review of multi criteria decision making (MCDM) towards sustainable renewable energy development**, Elsevier, Zhejiang University, China. 2016. Available at <http://dx.doi.org/10.1016/j.rser.2016.11.191. Accessed October 21st, 2022.

LOOTSMA, F., Scale sensitivity in the multiplicative AHP and SMART. Journal of Multi-Criteria Decision Analysis, pp. 87-110. 1993
MADEIRA J.G., ALVIM A.C.M., MARTINS V.B., MONTEIRO N.A., **Selection of a tool to decision making for site selection for high level waste**. EPJ Nuclear Sciences & Technologies 2016. Available at <https://doi.org/10.1051/epjn/e2015-50039-x>. Accessed October 23rd, 2022.

MAHER, C. J., **Current headend technologies and future developments in the reprocessing of spent nuclear fuels. Reprocessing and Recycling of Spent Nuclear Fuel**. Reprocessing and Recycling of Spent Nuclear Fuel(pp.93-124), Woodhead Publishing. Cambridge, United Kingdom. 2015. Available at <http://dx.doi.org/10.1016/B978-1-78242-212-9.00005-8>. Accessed October 23rd, 2022.

MAIA Y. L., **An approach for the site selection of an interim storage facility for the reactor compartment of the decommissioned Brazilian nuclear submarines.** 2022. Thesis of Doctorate. Federal Rio de Janeiro University. Available at <https://www.nuclear.ufrj.br/index.php/pt/producao-academica/doutorado/2022/2061-modelagem-computacional-para-avaliacao-das-condicoes-de-protecao-e-seguranca-de-uma-sala-de-radioterapia-8>. Accessed in February 26th 2023.

MAIA Y. L., MELO P. F. F. F., LINHARES T. Q., PINHO B. E., **Decommissioning of Nuclear Submarines and the Interim Storage of Their Reactor Compartments**. The American society of Mechanical engineers. USA. Available at <https://asmedigitalcollection.asme.org/risk/article-abstract/8/4/041103/1140302/Decommissioning-of-Nuclear-Submarines-and-the?redirectedFrom=PDF>. Accessed October 21st, 2022.

MARDANI A., JUSOH A., KHALIL MD NOR, KHALIFAH Z., ZAKWAN N. & VALIPOUR A., **Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014**, Economic Research-Ekonomskalstraživanja, Malasya. 2015. Available at <https://doi.org/10.1080/1331677X.2015.1075139>. Accessed June 13th, 2022.

MARTINS, V.B., **Metodologia baseada em sistemas de informação geográfica e análise multicritério para a seleção de áreas para a construção de um repositório para o combustível nuclear usado**, 2009, UFRJ, RJ, Brazil, accessed October 21st, 2022, http://antigo.nuclear.ufrj.br/DScTeses/teses2009/Tese_Vivian.pdf.

MILLET, I., HARKER, P.T., Globally effective questioning in the Analytic Hierarchy Process. European Journal of Operational Research 48. 1990.

MORKŪNAITĖ Z., KALIBATAS D., KALIBATIENĖ D., A BIBLIOMETRIC DATA ANALYSIS OF MULTI-CRITERIA DECISION MAKING METHODS IN HERITAGE BUILDINGS. 2019. Available at <https://doi.org/10.3846/jcem.2019.8315>Accessed in february 22nd 2023.

NEA/OECD, **Management and disposal of high-level radioactive waste: global progress and solutions**, Paris, France. 2020. Available at <https://www.oecd-nea.org/jcms/pl_32567/management-and-disposal-of-high-level-radioactive-waste-global-progress-and-solutions?details=true>. Accessed October, 21st, 2022.

NEA/OECD, **Nuclear Electricity Generation: What Are the External Costs?**, Paris, France. 2003. Available at <https://www.oecd-nea.org/jcms/pl_13756/nuclear-electricity-generation-what-are-the-external-costs?details=true>. Accessed October, 1st, 2022.

NEA/OECD, **The Economics of the Back End of the Nuclear Fuel Cycle**. 2013. Available at <https://www.oecd-nea.org/jcms/pl_14764/the-economics-of-the-back-end-of-the-nuclear-fuel-cycle?details=true>. Accessed in January 15th 2023.

NEA/OECD, Strategies and Considerations for the Back End of the Fuel Cycle © OECD 2021 NEA No. 7469 NUCLEAR ENERGY AGENCY ORGANISATION FOR, Paris, France. 2021. Available at <https://www.oecd-nea.org/upload/docs/application/pdf/2021-02/7469_best_report_2021-02-19_17-42-24_447.pdf>. Accessed March, 24th, 2023.

NODARI, C. J., SALDANHA, P. L. D.S., FONTES G. S., **Safety Aspects in Dry Storage of Spent Nuclear Fuel in Long Term Operation for Brazilian Nuclear Power Plants**. IEEE Latin America Transactions. New York, USA. 2021. Available at <https://latamt.ieeer9.org/index.php/transactions/article/view/3661>. Accessed October 21st, 2022.

NOH H., **A Study on Multilateral Management Options for Spent Nuclear Fuels in Northeast Asia Using Multi-criteria Evaluation, Department of Energy Systems Engineering**, Seoul National University, Seoul, South Korea. 2016. Available at <https://s-space.snu.ac.kr/bitstream/10371/118206/1/000000137519.pdf>. Accessed October 21st, 2022.

NUCLEAR ENGINEETING INTERNATIONAL – NEI, **Finland's path to final disposal of nuclear waste**. Available at <https://www.neimagazine.com/features/featurefinlands-path-to-final-disposal-of-nuclear-waste-9592096/> Accessed in April 07th 2023.

NUCNET, **Waste Management - Sweden / 'More Than 80%' Approve Of SKB's Spent Fuel Repository Plans**. Brussels, Belgium. 2020. Available at <https://www.nucnet.org/news/more-than-80-approve-of-skb-s-spent-fuel-repository-plans-5-3-2020>. Accessed October 21st, 2022,

OFFICE OF NUCLEAR ENERGY, **5 Fast Facts about Spent Nuclear Fuel**. 2022. Washington, USA. Available at <https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel>. Accessed October 26th, 2022.

OSTI, **International Approaches for Nuclear Waste Disposal in Geological Formations: Geological Challenges in Radioactive Waste Isolation**, DOE's Office of Scientific and Technical Information (OSTI) – LBNL. Oak Ridge, USA. 2016. Available at https://doi.org/10.2172/1353043>. Accessed October 21st, 2022.

OSTI, **Used Fuel Extended Storage Security and Safeguards by Design Roadmap**. Available at <https://www.osti.gov/servlets/purl/1341726>. Accessed January 15th 2023.

OSURI P.K.G.M., **Evaluation of Multi Criteria Decision Making Methods for Potential Use in Application Security**. School of Computing - Blekinge Institute of Technology, Karlskrona, Sweden. 2014. Available at <https://www.diva-portal.org/smash/get/diva2:831025/FULLTEXT01.pdf>. Accessed in October 21st, 2022.

PETRONOTÍCIAS, **Eletronuclear has completed the first stage of the transfer of spent fuels from ANGRA 2**. Rio de Janeiro, Brazil. 2021. Availableat<https://petronoticias.com.br/eletronuclear-concluiu-a-primeira-etapa-da-transferencia-de-combustiveis-usados-de-angra-2/>. Accessed October 21st, 2021.

PINHO, B. E., **Preliminary Plan for Decommissioning and Post Shutdown Activities of Brazilian NPPs**. IAEA Nucleus data. Vienna, Austria. 2018. Available at <https://nucleus.iaea.org/sites/connect/SFMpublic/TM%20Shutdown%20Reactor%20Sites/4.2%20Brazil_Eletrobras%20Eletronuclear_Estanqueira%20Pinho.pdf>. Accessed July 7th, 2021.

POINSSOT C., BOURG S., OUVRIER N., COMBERNOUX N., ROSTAING C., VARGAS-GONZALEZ M., BRUNO J., **Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles**. 2014. Available at <http://dx.doi.org/10.1016/j.energy.2014.02.069>. Accessed October 10th, 2022.

PROSPECT LAW, **High Level Radioactive Waste: Novel Geological Disposal Concept Proposed**, London, United Kingdom. 2019. Available at <https://prospectlaw.co.uk/high-level-radioactive-waste-novel-geological-disposal-concept-proposed/>. Accessed July 10th, 2022.

RABOSHAGA N.J.A., TSHANGELA A., ATOGO M., KESSEL D.S. AND KIM C.L., **Temporary Management of Spent Nuclear Fuel during Decommissioning of an NPP**. KEPCO International Nuclear Graduate School, Gyeongju, South Korea. 2016. Available at <https://www.kns.org/files/pre_paper/36/16A-409Nthato-Jay-Aar-Raboshaga.pdf>. Accessed October 21st, 2022.

RAMANATHAN R., GANESH L., Energy resource allocation incorporating qualitative and quantitative criteria: an integrated model using goal Programming and AHP. Elsevier Science Ltd. 1995.

RATIKO R., WISNUBROTO D.S., NASRUDDIN N., MAHLIA T.M.I., **Current and future strategies for spent nuclear fuel management in Indonesia**, Elsevier – ScienceDirect. 2020. Available at <https://doi.org/10.1016/j.esr.2020.100575>. Accessed October 21st, 2022.

RODRÍGUEZ-PENALONGA L. AND MORATILLA-SORIA B.Y., **Analysis of the costs of spent nuclear fuel management in Spain: The Marino model**. 2019. Available at <https://doi.org/10.1016/j.energy.2019.115853>. Accessed in January 15th 2023.

ROMANATO L. S., **Armazenagem de combustível nuclear "queimado"**. Instituto de Pesquisas Energéticas e Nucleares (IPEN). São Paulo, Brazil. 2005. Available at <https://inis.iaea.org/collection/NCLCollectionStore/_Public/39/084/39084483.pdf>. Accessed October, 21st, 2022.

SAATY L, T. and VARGAS L.G., **Models, Methods, Concepts & applications of The Analytic Hierarchy Process**. Springer. New York, NY, USA. 2001. Available at <http://dx.doi.org/10.1007/978-1-4615-1665-1>. Accessed October 21st, 2022,

SAATY T. L., **The Analytic Hierarchy Process**, McGraw-Hill, New York, NY, USA, 1980.

SAATY T.L. and GHOLAMNEZHAD H., **High-level nuclear waste management: analysis of options**. SAGE Journals. University of Pittsburgh, USA, 1982.

SAATY T.L., **A scaling method for priorities in hierarchical structures**, Journal of Mathematics Psychology, vol. 15, pp. 234-281, 1977.

SAATY T.L., **Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a complex world**. University of Pittsburgh, USA, 2012. Available at <https://doi.org/10.1068/b0901>. Accessed October 23rd, 2022.

SAŁABUN W., WATRÓBSKI J. AND SHEKHOVTSOV A., **Are MCDA Methods Benchmarkable? A Comparative Study of TOPSIS, VIKOR, COPRAS, and PROMETHEE II Methods**. Available at <https://www.mdpi.com/2073-8994/12/9/1549>. Accessed October 20th, 2022.

SCHWENK-FERRERO A. AND ANDRIANOV A, **Nuclear Waste Management Decision-Making Support with MCDA**. HIDAwi – Science and Technology of Nuclear Installations, London, United Kingdom. 2017.Available at <https://doi.org/10.1155/2017/9029406. Accessed October 20th 2022.

SKB International AB - SKB, The Government approves SKB's final repository system. Available at <https://www.skb.com/news/the-government-approves-skbs-final-repository-system/>. Accessed April 04th 2023.

STIMSON, **Spent Nuclear Fuel Storage and Disposal**. Washington, USA. 2022. Available at <https://www.stimson.org/2020/spent-nuclear-fuel-storage-and-disposal/>. Accessed October 14th 2022.

TAJI K, LEVY J. K., HARTMANN J., BELL M. L., ANDERSON R. M., HOBBS B. F., FEGLAR T., **Identifying potential repositories for radioactive waste: multiple criteria decision analysis and critical infrastructure systems**. 2005. Department of Mechanical Science and Engineering, Nagoya University, Japan. Available at <https://www.researchgate.net/publication/220592972_Identifying_potential_repositories_for_radioactive_waste_Multiple_criteria_decision_analysis_and_critical_infrastructure_systems>. Accessed in September 3rd 2022.

TAYLOR, J. ROBIN ET AL. **Reprocessing and Recycling of Spent Nuclear Fuel**. 1st edition, Woodhead Publishing Series in Energy. United Kingdom. 2015.

TCU, **Levantamento sobre gerenciamento seguro de rejeitos radioativos e de combustível nuclear usado**. 2014. Available at <https://pesquisa.apps.tcu.gov.br/#/documento/acordao-completo/AC-1108-14%252F14-P/%2520/DTRELEVANCIA%2520desc%252C%2520NUMACORDAOINT%2520desc/0/%2520 <. Accessed October 17th,2022.

TCU 1, orientações para elaboração de planilhas orçamentárias de obras públicas. 2014. Available at <https://portal.tcu.gov.br/data/files/BF/21/7F/EE/965EC710D79E7EB7F18818A8/Orientacoes_elaboracao_planilhas_orcamentarias_obras_publicas.PDF> . <. Accessed May 14th, 2024.

TOLOI, R. C., REIS, J. G. M., TOLOI, M. N. V., VENDRAMETTO, O., CABRAL, J. A. S. P., **Applying Analytic Hierarchy Process (AHP) to identify decision-making in soybean supply chains: a case of Mato Grosso production**. Revista de Economia e Sociologia Rural. Mato Grosso, Brasil. 2022. Available at <https://doi.org/10.1590/1806-9479.2021.229595 >. Accessed October 21st, 2022.

TRIANTAPHYLLOU E., **Multi-criteria Decision-Making Methods: A Comparative Study**, Springer New York, New York, USA, 2000. Available at <https://doi.org/10.1007/978-1-4757-3157-6>. Accessed October 21st, 2022.

U.S.NRC, **Final Safety Evaluation Report Related to Certification of the AP1000 Standard Plant Design Docket No. 52-006**. Available at <https://dms.psc.sc.gov/Attachments/Matter/9ff81e46-8063-4a8d-9590-d1d5c2cd94ac>. Accessed January 07th, 2023.

U.S.NRC., **Glossary: Decommissioning characterization**. Washington, USA. 2019. Available at <https://www.nrc.gov/reading-rm/basic-ref/glossary/decommissioning.html>. Accessed March 23rd, 2019.

U.S.NRC., **Storage of Spent Nuclear Fuel.** Washington, USA. 2021. Available at <https://www.nrc.gov/waste/spent-fuel-storage.html. Accessed November 20th, 2021.

V. TSYGANOK *et al.*, **Significance of Expert Competence Consideration in Group Decision Making using AHP**. 2012. Available at <http://www.isahp.org/uploads/154_078_tsyganok.pdf>. Accessed February 19th 2023.

WESTINGHOUSE, **AP1000 Plant Design**. 2023. Available at <https://www.westinghousenuclear.com/energy-systems/ap1000-pwr/overview>. Accessed January 07th, 2023.

WINDARTO A. P. AND MUHAMMAD A., **Comparison of Weighted Sum Model and Multi Attribute Decision Making Weighted Product Methods in Selecting the Best Elementary School in Indonesia**. International Journal of Software Engineering and Its Applications. pp. (69-90). Indonesia. Available at <http://dx.doi.org/10.14257/ijseia.2017.11.4.0>. Accessed October 23rd, 2022.

WNA 1, **Decommissioning Nuclear Facilities**. London, United Kingdom. 2021. Available at <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx>. Accessed April 28th 2021.

WNA 2, **Processing of Used Nuclear Fuel**. London, United Kingdom. 2021. Available at <https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx>. Accessed October 21st 2022.

WNA 3, **Storage and Disposal of Radioactive Waste**. London, United Kingdom. 2021. Available at <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste.aspx#:~:text=Disposal%20of%20low%2Dlevel%20waste,the%20most%20radioactive%20waste%20produced>. Accessed October 26th, 2022.

WNA, **The Nuclear Debate.** London, United Kingdom. 2022. Available at <https://world-nuclear.org/information-library/current-and-future-generation/the-nuclear-debate.aspx>. Accessed October 22nd, 2022.

WNA, **WNA response to the International Energy Agency's Net Zero by 2050 report**. London, United Kingdom. 2022. Available at <https://www.world-nuclear.org/press/press-statements/world-nuclear-association-response-to-the-internat.aspx. Accessed October 22nd, 2022.

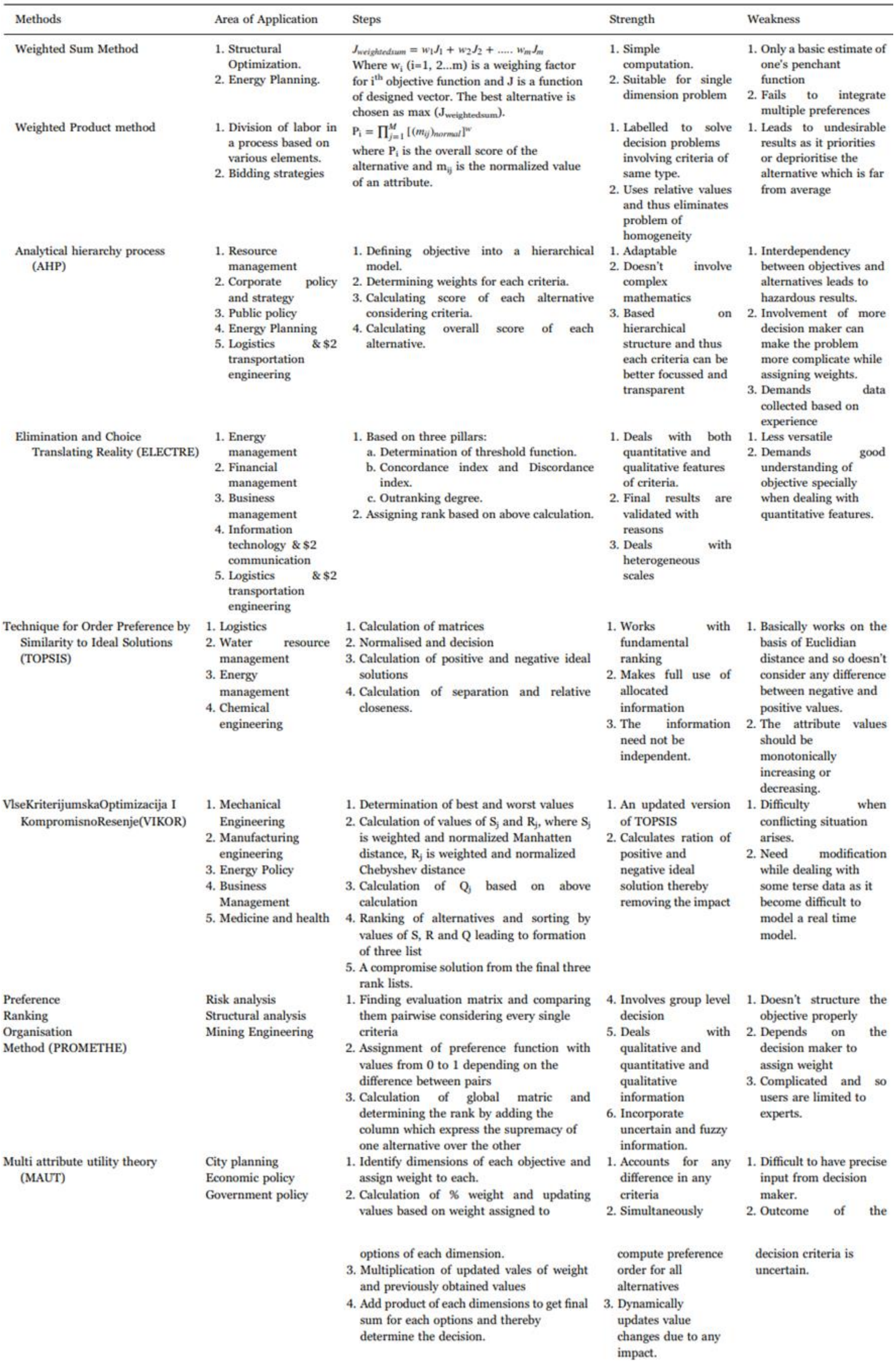
WNA, **World Nuclear News - Construction of test disposal tunnel under way at Onkalo**. London, United Kingdom. 2022. Available at <https://world-nuclear-news.org/Articles/Construction-of-test-disposal-tunnel-under-way-at>. Accessed 22nd, 2022.

WNN, Brazil AP1000 collaboration for Westing House. 19th June of 2015. Available at <https://www.world-nuclear-news.org/Articles/Brazilian-AP1000-collaboration-for-Westinghouse>. Accessed January 07th, 2023.

YOON S., CHOI S., KO W., **An Integrated Multicriteria Decision-Making Approach for Evaluating Nuclear Fuel Cycle Systems for Long-term Sustainability on the Basis of an Equilibrium Model: Technique for Order of Preference by Similarity to Ideal Solution, Preference Ranking Organization Method for Enrichment Evaluation, and Multi-attribute Utility Theory Combined with Analytic Hierarchy Process**. Korea University of Science and Technology, ScienceDirect, Korea. 2016. Available at <http://dx.doi.org/10.1016/j.net.2016.07.009>. Accessed October 22nd, 2022.

ZLAUGOTNE B., ZIHARE L., BALODE L., KALNBALKITE A., KHABDULLIN A., BLUMBERGA D., **Multi-Criteria Decision Analysis Methods Comparison, Environmental and Climate Technologies**. Sciendo RIGA Technical University, Warsaw, Poland. 2020. Available at <https://doi.org/10.2478/rtuect-2020-0028>. Accessed April 5th, 2022.

APPENDIX A - MCDM methods, their application, strength, and weakness [KUMAR et al, 2016]



Methods	Area of Application	Steps	Strength	Weakness
Weighted Sum Method	1. Structural Optimization. 2. Energy Planning.	$J_{weightedsum} = w_1J_1 + w_2J_2 + ... w_mJ_m$ Where w_i (i=1, 2...m) is a weighing factor for i^{th} objective function and J is a function of designed vector. The best alternative is chosen as max ($J_{weightedsum}$).	1. Simple computation. 2. Suitable for single dimension problem	1. Only a basic estimate of one's penchant function 2. Fails to integrate multiple preferences
Weighted Product method	1. Division of labor in a process based on various elements. 2. Bidding strategies	$P_i = \prod_{j=1}^{M} [(m_{ij})_{normal}]^w$ where P_i is the overall score of the alternative and m_{ij} is the normalized value of an attribute.	1. Labelled to solve decision problems involving criteria of same type. 2. Uses relative values and thus eliminates problem of homogeneity	1. Leads to undesirable results as it priorities or deprioritise the alternative which is far from average
Analytical hierarchy process (AHP)	1. Resource management 2. Corporate policy and strategy 3. Public policy 4. Energy Planning 5. Logistics & $2 transportation engineering	1. Defining objective into a hierarchical model. 2. Determining weights for each criteria. 3. Calculating score of each alternative considering criteria. 4. Calculating overall score of each alternative.	1. Adaptable 2. Doesn't involve complex mathematics 3. Based on hierarchical structure and thus each criteria can be better focussed and transparent	1. Interdependency between objectives and alternatives leads to hazardous results. 2. Involvement of more decision maker can make the problem more complicate while assigning weights. 3. Demands data collected based on experience
Elimination and Choice Translating Reality (ELECTRE)	1. Energy management 2. Financial management 3. Business management 4. Information technology & $2 communication 5. Logistics & $2 transportation engineering	1. Based on three pillars: a. Determination of threshold function. b. Concordance index and Discordance index. c. Outranking degree. 2. Assigning rank based on above calculation.	1. Deals with both quantitative and qualitative features of criteria. 2. Final results are validated with reasons 3. Deals with heterogeneous scales	1. Less versatile 2. Demands good understanding of objective specially when dealing with quantitative features.
Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)	1. Logistics 2. Water resource management 3. Energy management 4. Chemical engineering	1. Calculation of matrices 2. Normalised and decision 3. Calculation of positive and negative ideal solutions 4. Calculation of separation and relative closeness.	1. Works with fundamental ranking 2. Makes full use of allocated information 3. The information need not be independent.	1. Basically works on the basis of Euclidian distance and so doesn't consider any difference between negative and positive values. 2. The attribute values should be monotonically increasing or decreasing.
VlseKriterijumskaOptimizacija I KompromisnoResenje(VIKOR)	1. Mechanical Engineering 2. Manufacturing engineering 3. Energy Policy 4. Business Management 5. Medicine and health	1. Determination of best and worst values 2. Calculation of values of S_j and R_j, where S_j is weighted and normalized Manhatten distance, R_j is weighted and normalized Chebyshev distance 3. Calculation of Q_j based on above calculation 4. Ranking of alternatives and sorting by values of S, R and Q leading to formation of three list 5. A compromise solution from the final three rank lists.	1. An updated version of TOPSIS 2. Calculates ration of positive and negative ideal solution thereby removing the impact	1. Difficulty when conflicting situation arises. 2. Need modification while dealing with some terse data as it become difficult to model a real time model.
Preference Ranking Organisation Method (PROMETHE)	Risk analysis Structural analysis Mining Engineering	1. Finding evaluation matrix and comparing them pairwise considering every single criteria 2. Assignment of preference function with values from 0 to 1 depending on the difference between pairs 3. Calculation of global matric and determining the rank by adding the column which express the supremacy of one alternative over the other	4. Involves group level decision 5. Deals with qualitative and quantitative and qualitative information 6. Incorporate uncertain and fuzzy information.	1. Doesn't structure the objective properly 2. Depends on the decision maker to assign weight 3. Complicated and so users are limited to experts.
Multi attribute utility theory (MAUT)	City planning Economic policy Government policy	1. Identify dimensions of each objective and assign weight to each. 2. Calculation of % weight and updating values based on weight assigned to options of each dimension. 3. Multiplication of updated vales of weight and previously obtained values 4. Add product of each dimensions to get final sum for each options and thereby determine the decision.	1. Accounts for any difference in any criteria 2. Simultaneously compute preference order for all alternatives 3. Dynamically updates value changes due to any impact.	1. Difficult to have precise input from decision maker. 2. Outcome of the decision criteria is uncertain.

APPENDIX B - MCDA Methods Summary - adapted from [ZLAUGOTNE et al., 2020]

	AHP	TOPSIS	VIKOR	COPRAS	MULTIMOORA	PROMETHEE-GAIA
TYPE OF NORMALIZATION	VECTOR NORMALISATION (SUM)	VECTOR NORMALISATION (SQUARE ROOT OF SUM L2 NORMALIZATION)	LINEAR NORMALIZATION (L1 NORMALIZATION)	VECTOR NORMALIZATION (SUM)	VECTOR NORMALIZATION (SQUARE ROOT OF SUM)	NORMALIZATION IS PERFORMED AUTOMATICALLY
SUITABILITY	CHOICE PROBLEMS, RANKING PROBLEMS, SORTING PROBLEMS (AHPsort)	CHOICE PROBLEMS, RANKING PROBLEMS	CHOICE PROBLEMS, RANKING PROBLEMS	CHOICE PROBLEMS, RANKING PROBLEMS	CHOICE PROBLEMS, RANKING PROBLEMS	CHOICE PROBLEMS, RANKING PROBLEMS, DESCRIPTIONS PROBLEMS (GAIA)
INPUTS	PAIRWISE COMPARISON ON RATIO SCALE (1-9)	IDEAL AND ANTI-IDEAL OPTION WEIGHTS	BEST AND WORST OPTION WEGHTS	BEST AND WORST OPTION WEGHTS	BEST AND WORST OPTION WEGHTS	INDIFFERENCE AND PREFERENCE THRESHOLDS WEIGHTS
OUTPUTS	COMPLETE RANKING WITH SCORES	COMPLETE RANKING WITH CLOSENESS SCORE TO IDEAL AND DISTANCE TO ANTI-IDEAL	COMPLETE RANKING WITH CLOSENESS SCORE TO BEST OPTION	COMPLETE RANKING	COMPLETE RANKING	PARTIAL AND COMPLETE RANKING PAIRWISE OUTRANKING DEGREES
APPROACH	QUALITATIVE	QUALITATIVE AND/OR QUANTITATIVE	QUANTITATIVE	QUANTITATIVE	QUANTITATIVE	QUALITATIVE AND/OR QUANTITATIVE
CONSISTENCY LEVELS	9	NO RESTRICTIONS	NO RESTRICTIONS	NO RESTRICTIONS	NO RESTRICTIONS	7 ± 2
SOFTWARE	MS EXCEL, MAKE IT RATIONAL, EXPERT CHOICE, DECISION LENS, HIPRE 3+, RIGHT CHOICE DSS, CRITERIUM, EASY MIND, QUESTFOX, CHOICE RESULTS, B14 AHP, DECERNS	MS EXCEL, MATLAB, DECERNS	MS EXCEL	MS EXCEL	MS EXCEL	VISUAL PROMETHEE, DECISION LAB, D-SIGHT, SMART PICKER PRO

APPENDIX C - Spent Fuel Management Strategies around World

COUNTRY	COMMERCIAL SCALE REPROCESSING FACILITY		SPENT FUEL CURRENTLY IN ANOTHER COUNTRY FOR REPROCESSING	EARLIER REPROCESSING, BUT PRACTICE CURRENTLY CEASED	PLANNING DIRECT PLACEMENT OF SPENT FUEL IN A REPOSITORY	KEEPING OPTIONS OPEN
	EXISTING	PLANNED				
ARGENTINA						X
BELGIUM				X	X	X
BRAZIL						X
BULGARIA			X			
CANADA					X	
CHINA		X			X	
CZECH REPUBLIC				X	X	
FINLAND				X	X	
FRANCE	X					
GERMANY				X	X	
HUNGARY				X	X	
INDIA	X	X				
ITALY			X			
JAPAN		X	X			
KOREA, REPUBLIC						X
LITHUANIA					X	
MEXICO						X
NETHERLANDS			X			
ROMANIA					X	
RUSSIAN FEDERATION	X	X				
SLOVAKIA				X	X	
SLOVENIA					X	
SPAIN				X	X	
SWEDEN				X	X	
SWITZERLAND				X	X	
TURKEY					X	
UK	X			X	X	
UKRAINE			X	X		X
USA				X	X	

APPENDIX D - Cost estimation of the Brazilian nuclear fuel cycle back-end by installation in $2019 Million adapted from [JONUSAN, 2021]

Facility	**Cost case**	**Angra 1 + Angra 2 + Angra 3**		**ANGRA 1 + Angra 2 + Angra 3 +8 NPPs**	
		OFC	**CFC**	**OFC**	**CFC**
Interim Storage Facility Oversight investment	Low	504,68	525,95	960,24	1033,71
	Reference	728,77	774,8	1714,74	1873,74
	High	978,61	1049,42	2495,15	2739,71
Interim storage facility: O&M	Low	11,78	12,36	13,81	14,05
	Reference	15,56	15,77	20,11	20,84
	High	20,2	20,55	27,78	29
Integrated reprocessing plant: Overnight investment	Low	-	5337,55	-	5660,04
	Reference	-	7207,08	-	7633,68
	High	-	8911,19	-	9449,57
Integrated reprocessing plant: O&M	Low	-	421,23	-	433,51
	Reference	-	506,72	-	521,67
	High	-	591,15	-	608,7
SNF encapsulation plant: Overnight investment	Low	187,45	221,53	378,29	336,73
	Reference	249,93	295,37	504,38	448,98
	High	312,41	369,21	630,48	561,22
SNF encapsulation plant: O&M	Low	18,57	20,72	30,65	28,02
	Reference	24,75	27,63	40,87	37,36
	High	30,94	34,54	51,09	46,7
Geological repository: Overnight investment	Low	952,2	951,43	1460,41	1456,26
	Reference	2375,6	2,373,65	3650,28	3639,86
	High	6557,79	6552,47	10053,57	10025
Geological repository: O&M	Low	24,01	23,99	39,63	39,51
	Reference	78,09	78,06	95,06	94,92
	High	204,22	204,19	224,36	224,2
Geological repository: Closure	Low	235,4	235,4	235,4	235,4
	Reference	470,8	470,8	470,8	470,8
	High	1412,4	1412,4	1412,4	1412,4
Transport	Low	0,02	0,02	0,02	0,02
	Reference	0,06	0,06	0,06	0,06
	High	0,16	0,16	0,16	0,16