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MASTER IN ENVIRONMENT AND SMART ENERGY MANAGEMENT

MASTER'S FINAL PROJECT

The fourth R in Nuclear Technology

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Director: B. Yolanda Moratilla Soria

Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

La cuarta R de la tecnología nuclear: Reprocesado

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2020/21 es de mi autoría, original e inédito y

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Fdo.: Marta Velasco Estévez Fecha: 19/08/2021

Autorizada la entrega del proyecto

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LA CUARTA R DE LA TECNOLOGÍA NUCLEAR: REPROCESADO

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RESUMEN DEL PROYECTO

1. Introducción

La sociedad actual, preocupada por los problemas medioambientales que se han acentuado las últimas décadas, se ha concienciado acerca de la necesidad de descarbonizar la sociedad. Aunque una sociedad descarbonizada se confunde en ocasiones con una sociedad electrificada, son conceptos diferentes puesto que hay otros vectores energéticos, como el vector hidrógeno actualmente en auge, que permiten descarbonizar el sistema. Son varias las tecnologías que conducen hacia este objetivo y entre ellas destaca la energía nuclear, que permite producir energía sin emitir gases de efecto invernadero [1].

Una correcta gestión de los residuos nucleares es fundamental para decantar la balanza a favor de esta tecnología. La producción de residuos es inherente a la actividad industrial y su gestión es una etapa imprescindible, siendo una de las prioridades de los grupos de investigación que buscan optimizar gestión de residuos de alta actividad, con el objetivo futuro de lograr que no existan residuos nucleares gracias a los ciclos avanzados que permiten separar los componentes del combustible nuclear gastado y así poder ser reutilizados como materias primas.

2. Definición del proyecto

Se busca justificar la necesidad de mantener en España la energía nuclear como parte del mix energético, tanto por razones técnicas de estabilidad del sistema como por razones económicas para evitar la escalada de la pobreza energética. Además, se va a demostrar la aceptabilidad social a esta tecnología, siempre y cuando se renueve la imagen anticuada de los cementerios nucleares gracias a la utilización de tecnologías más de vanguardia, desarrolladas en línea con la regla de las 4R. Estas tecnologías, al igual que el slogan medioambiental citado anteriormente, buscan optimizar el aprovechamiento de materias primas gracias el reprocesado y posterior reciclaje y reutilización de materiales, no solo en la fase convencional actual sino avanzando tendencias económicas de invertir en el nuevo modelo de reprocesado que permite separar más isótopos.

3. Metodología

Con el fin de analizar la viabilidad económica del reprocesado avanzado, se estima el incremento en el coste del reprocesado avanzado con respecto al reprocesado convencional, a partir de los datos obtenidos en la tesis doctoral de Laura Rodríguez [2]. El objetivo es demostrar que el reprocesado avanzado podría ser una opción viable para la gestión de residuos en un futuro próximo, pasando a formar parte de las posibles estrategias españolas para la gestión de CNG.

El estudio de la aceptabilidad social se realiza mediante encuestas enviadas a diferentes segmentos de la población y su posterior análisis. Dicha encuesta se redacta con el objetivo de preguntar de forma indirecta sobre la preferencia de la población encuestada entre una gestión de residuos nucleares con ciclo abierto o dicha gestión en ciclo cerrado.

4. Resultados

4.1. Estudio económico

Para realizar el estudio se consideran las siguientes hipótesis: no se realiza ningún pago por el Pu obtenido -1-, se establece un reprocesado avanzado en el que se extrae, aparte de U y Pu, algunos lantánidos y actínidos -2-, y, por último, se consideran estos elementos extraídos materias primas que pueden ser introducidas al mercado energético obteniendo de ello un beneficio. Con estas hipótesis definidas y consultando en la bibliografía el sobrecoste esperado de este reprocesado avanzado, se obtienen los costes totales para un incremento del 5%, 10% y 15%, mostrado en la Tabla 1, representando su tendencia en la Ilustración 1, donde se aprecia una tendencia lineal y un incremento en el coste de alrededor de 350 € cada incremento de 5% con respecto al reprocesado convencional.

	0%	***5%***	***10%***	***15%***
Coste total	9.277,93 M€	9.632,21 M€	9.986,48 M€	10.340,75 M€

Tabla 1. *Análisis de costes del reprocesado avanzado con respecto al coste del actual reprocesado.*

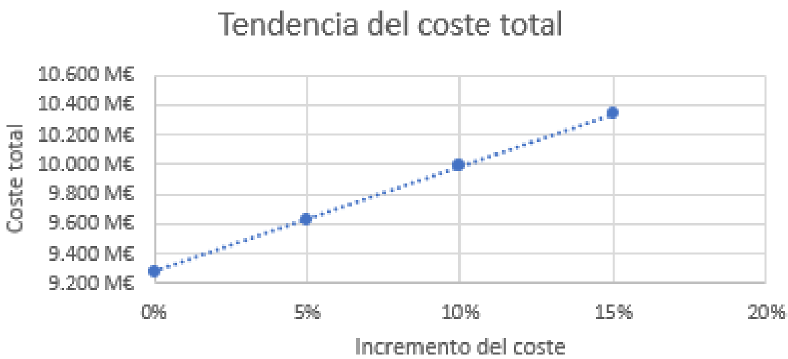

***Ilustración 1**. Tendencia del coste del reprocesado avanzado*

Aunque este es un coste aproximado, se debe tener en cuenta que este sobrecoste, en gran medida, se va a compensar con la venta de las materias primas recicladas, con la disminución del volumen de residuos que retornan a los países que enviaron su CNG a plantas de reprocesado avanzado (así como la disminución de la radioactividad de estos, lo que reduce también las exigencias radiológicas a la hora de diseñar los AGPs y los ATCs), y con la reducción de transporte derivada de la reducción en el volumen de los residuos.

4.2. Estudio de aceptabilidad social

La encuesta realizada mediante el método CAWI (*Computer Assisted Web Interviewing*), consta de un total de cinco preguntas. A continuación, se muestran las preguntas (excluyendo la quinta que era solo para analizar la franja de edad) y sus correspondientes respuestas en las Ilustraciones 2-5.

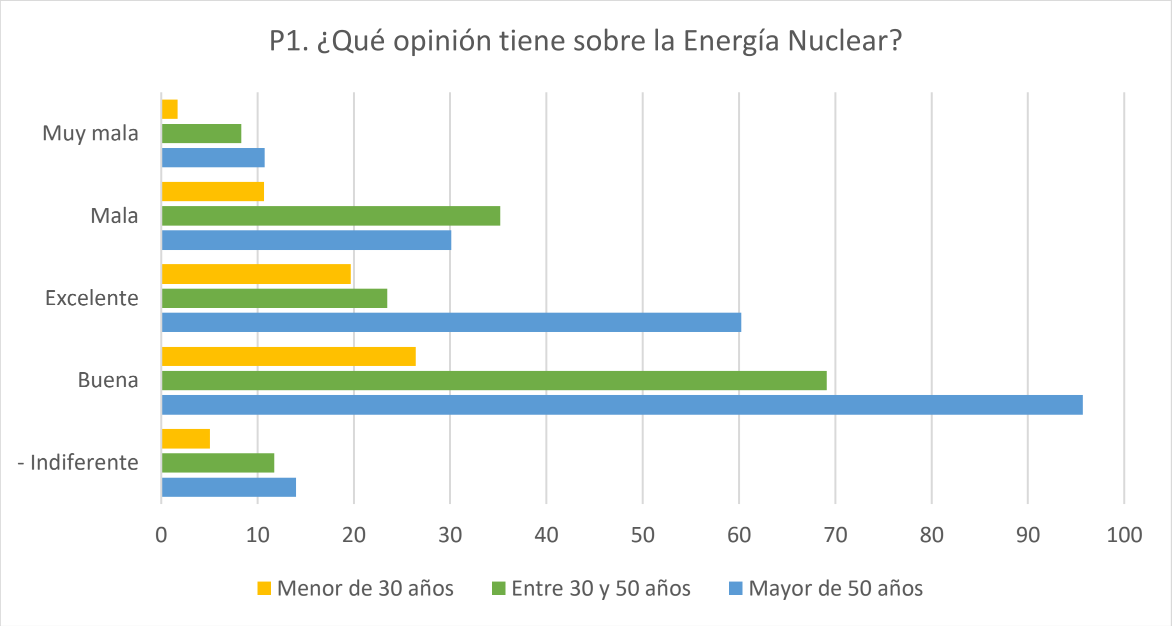

***Ilustración 2**. Respuestas a la pregunta 1 de la encuesta en función del rango de edades.*

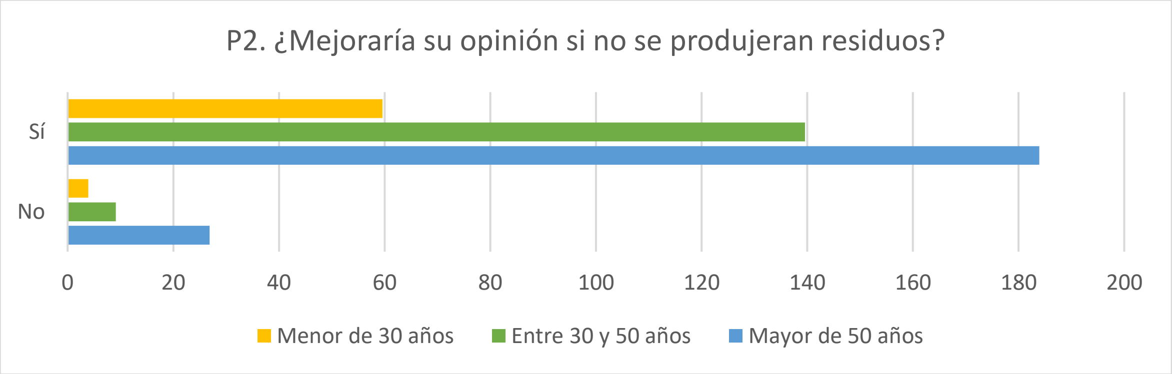

***Ilustración 3**. Respuestas a la pregunta 2 de la encuesta en función del rango de edades.*

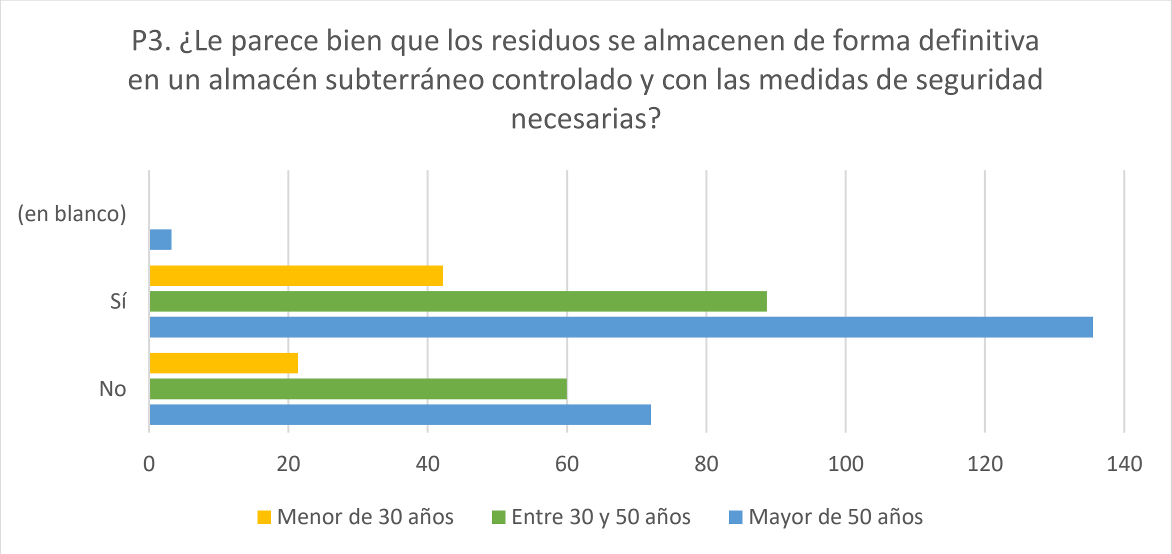

***Ilustración 4.** Respuestas a la pregunta 3 de la encuesta en función del rango de edades.*

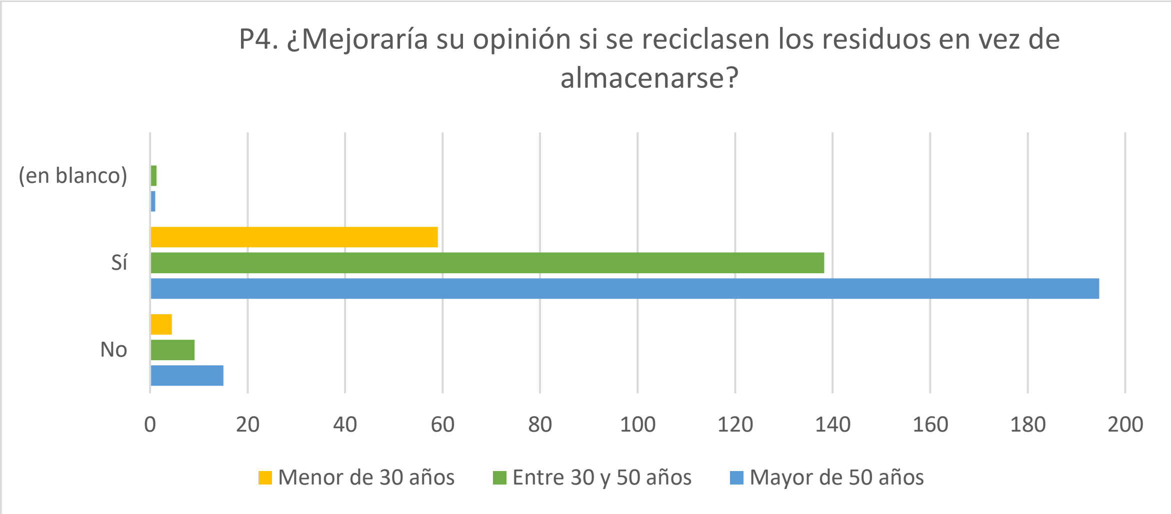

***Ilustración 5**. Respuestas a la pregunta 4 de la encuesta en función del rango de edades.*

Analizando las respuestas se puede afirmar que el ciclo abierto no convence ni si quiera a todos los que están a favor de emplear la energía nuclear ya que el 64% afirma estar de acuerdo con el almacén directo de residuos frente al 71% que se declara a favor de la energía nuclear. También se puede concluir que el empleo de un ciclo cerrado como estrategia para la gestión de residuos nucleares reduce significativamente la percepción negativa que tiene la población sobre la energía nuclear ya que el 22% de la población tiene una opinión negativa a cerca de esta fuente de energía y tan solo el 7% declara que el uso del ciclo cerrado no mejoraría su percepción. Cabe destacar que dentro de este 7% que no vería su opinión alterada, un 5% tenía una opinión "muy mala" acerca de la energía nuclear, lo que hace pensar que esta oposición es una oposición ideológica más que fundamentada en realidades tecnológicas. En esta línea, tan solo un 2% de los jóvenes menores de 30 declararon tener una opinión "muy mala" de la energía nuclear, lo que, unido al hecho de que este rango de edad está compuesto en su mayoría por estudiantes de ingenierías, da a entender que los jóvenes formados en esta área, con una opinión fundamentada en aspectos técnicos a priori, no presentan tanta oposición hacia esta tecnología como las personas adultas.

Por último, no se puede valorar a partir de las preguntas realizadas si alguna de las personas a los que no les convence el ciclo abierto basan esta opinión en una argumentación económica debida al sobrecoste que este ciclo conlleva.

5. Conclusiones

El cese total de las centrales nucleares españolas es una acción irreversible, puesto que no sería viable económicamente abrir nuevas centrales nucleares una vez clausuradas todas las que están operativas actualmente. Es por ello por lo que debe ser una decisión premeditada y que sopese todas las consecuencias.

Con el contexto actual europeo, analizando la posición de Alemania y Francia respecto a la energía nuclear, y el estudio realizado en el presente proyecto, queda demostrado que la tecnología nuclear es una tecnología clave para seguir con un sistema eléctrico estable y sin reducir las emisiones de gases de efecto invernadero. Esto hace que sea muy recomendable mantener las centrales nucleares españolas en operación, asegurando el suministro eléctrico las 24h del día, alineándose con el reto de alcanzar una sociedad descarbonizada, sin poner en peligro los avances tecnológicos e industriales debido a probables cortes de suministro de forzar su cierre. La disponibilidad, la fiabilidad, la estabilidad y la predictibilidad que ofrece posibilita una adecuada gestión del sistema eléctrico.

6. Referencias

[1] Bataille C, Waisman H, Colombier M, Segafredo L, Williams J. The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. Climate Policy. 2016;16(sup1): S1-S6.

[2] L. Rodríguez Penalonga, Modelo para la gestión sostenible del combustible nuclear gastado, 2020.

THE FOURTH R IN NUCLEAR TECHNOLOGY - REPROCESING

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Collaborating Entity: ICAI – Universidad Pontificia Comillas

SUMMARY OF THE PROJECT

1. Introduction

Current society, worried by the environmental crisis, is more compromised with the need of decarbonization of the system. Despite a decarbonized society is often mixed with an electrified society, those are very different concepts as there are other energetic vectors such as hydrogen energy. European Union is creating a portfolio of those environmentally sustainable technologies, and despite not being included yet, the nuclear energy could be a great ally as it can produce energy without emitting any greenhouse effect gas.

A proper management of the nuclear residues is fundamental to tip off the balance in favor to nuclear technology. The production of residues is inherent to the industrial activity and thus its management is key, needing to optimize those processes with the goal of achieving no nuclear residues production in the future, and reusing the components as new raw materials.

2. Project definition

This project aims to justify the need of nuclear technology in Spain as part of the energetic mix, both for system stability and economical reasons to about the rise of energetic poverty. Furthermore, it will show that the social acceptability of this technology can increase as long as the development in refinement and reuse of residues advances, in line with the rule of the 4R. These technologies, like the environmental slogan previously cited, look for an optimization of the raw materials thanks to the reprocessing, recycling and reuse of materials.

3. Model description

To analyze the economic feasibility of the advanced reprocessing, we estimated the increment in costs of the advanced process compared to the cost of conventional reprocessing. Such estimation was made from the data obtained in the PhD thesis of Laura Rodriguez. The goal of such calculation was to demonstrate that an advance reprocessing could be a feasible option for the waste management in a near future, thus becoming part of the portfolio of possible strategies for Spain to improve SNF management.

In order to assess the current opinion of the Spanish population regarding nuclear energy and its impact in the environment, a CAWI survey (Computer Assisted Web Interviewing) was designed with the five, below stated questions that could be answered in the scale from “excellent” to “very poor” or with a “yes/no” answer type.

4. Results

4.1. Economical study

When doing this analysis, the following hypothesis were held: (1) there is no associated payment for the plutonium obtained; (2) there is an advanced reprocessing in which lanthanoids and actinoids are obtained as well, alongside plutonium and uranium, and (3) the lanthanoids and actinoids obtained would be considered as raw material that put back in the market give an economical benefit.

With these defined hypotheses and using the literature to find the estimated over-cost of the advanced reprocessing, we obtained the total cost for an increment of 5%, 10% and 15%, showed in Table 1. representing the trend in Figure 1, where it can be seen as linear and with an increment of cost of around 350€ each increment of 5% compared to conventional reprocessing.

	0%	*5%*	*10%*	*15%*
Total Cost	9.277,93 M€	9.632,21 M€	9.986,48 M€	10.340,75 M€

Table 1. *Analysis of the advanced reprocessing cost compared to the current cost of reprocessing.*

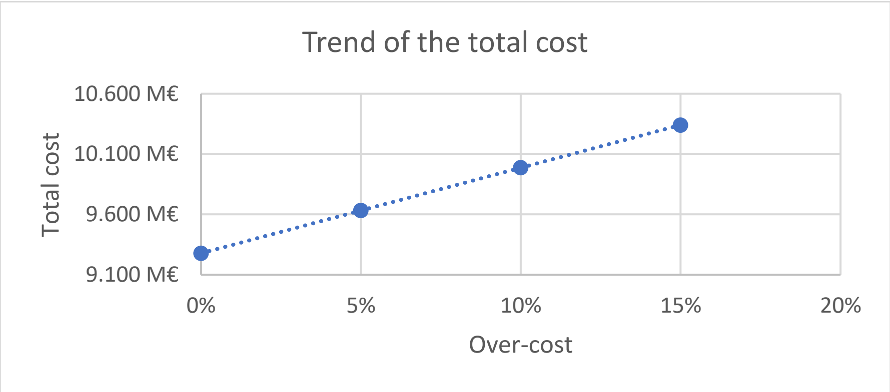

Figure 1: *Linear trend of over-cost against total cost*

Although this is an approximate cost, it has to be taken into account that the over-cost will largely be compensated with the sale of recycled raw materials, with the decrease in the residue volume that need to get back to their countries, and with the decrease in the transport need associated to this lower volume of residues.

4.1. Social acceptability

The survey performed by CAWI (*Computer Assisted Web Interviewing*) method consist of a total of five questions. Below, it is shown all the questions but the fifth one (only needed to set the age frame of the subject) and the corresponding answers.

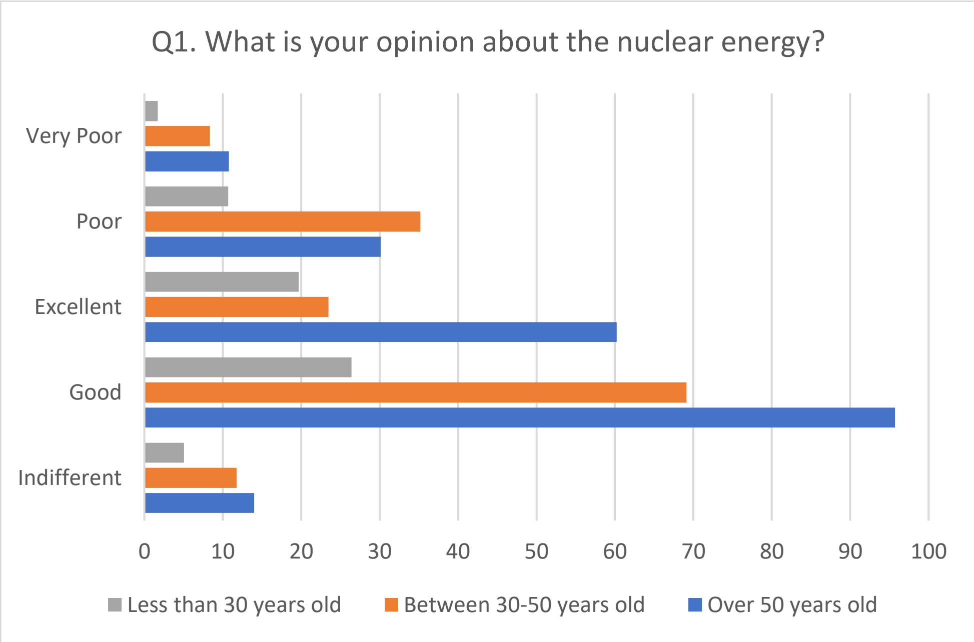

Figure 2: *Answers to Q1 grouped by age.*

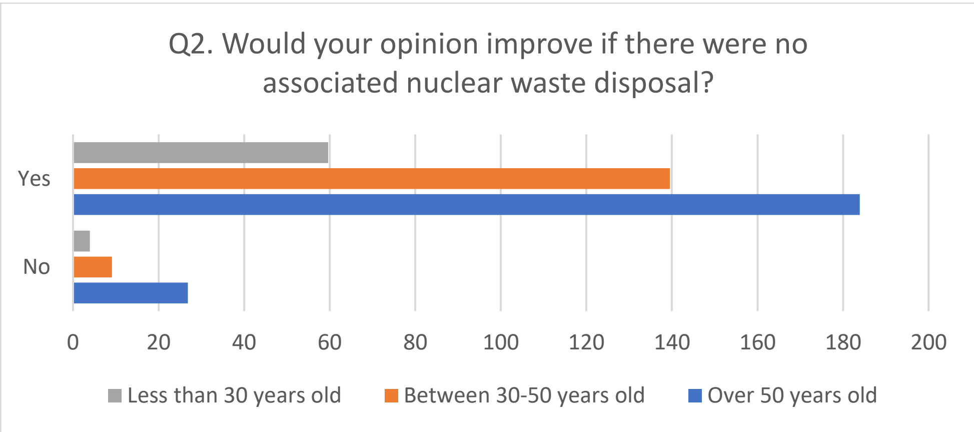

Figure 3: *Answers Q2 classified by age groups.*

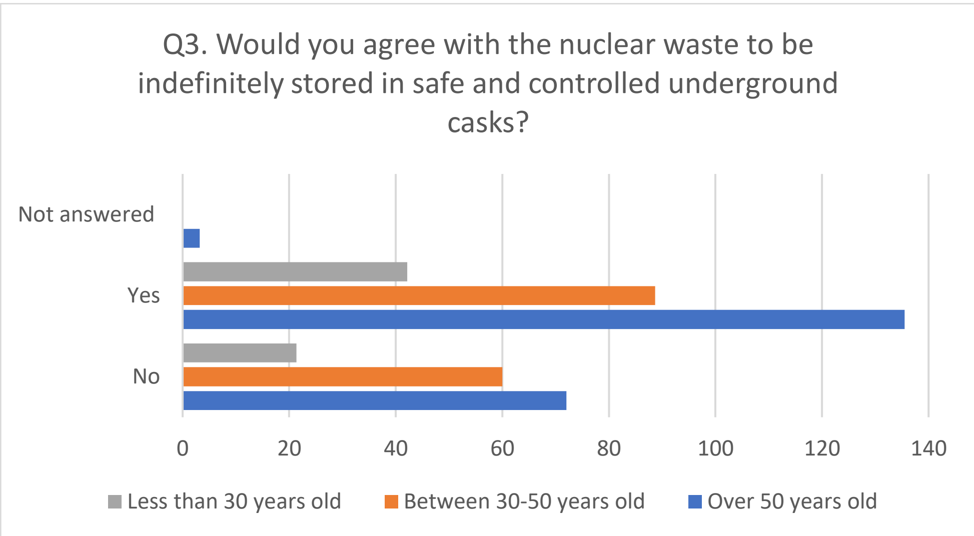

Figure 4: *Answers to Q3 classified by age groups.*

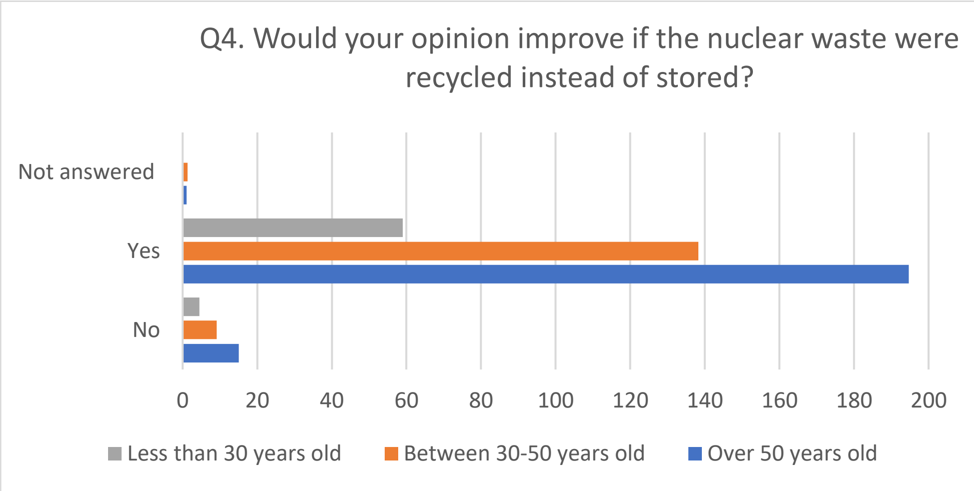

Figure 5: *Answers to Q4 classified by age groups.*

Based on all the answers collected, it is clear that a once-through cycle is not good enough for the population, not even for those who already hold a positive view of nuclear power (71% of population has a positive view of nuclear energy, while 64% agrees with the direct storage of SNF). On the other hand, it was also observed that the usage of a twice-through cycle as SNF management strategy would significantly reduce the negative perception of the surveyed sample. This affirmation is held on the basis that 22% of the population answered to have a negative perception of nuclear energy and only 7% of them declared that a change of the SNF management strategy would not be enough for them to improve their opinion about nuclear. It is worth noting that inside that 7% who would not change their opinion, 5% had a "very poor" view of nuclear technology, which leads to the hypothesis that such opposition is funded upon ideological fundaments rather than technological knowledge. Following this line, only the 2% of the people below 30 years old declared to have a "very poor" opinion about nuclear technology, and this, linked to the fact that most people belonging to this sample group are engineering students, leads to the hypothesis that when having the grounds and knowledge about what is nuclear technology and how it works, people is less inclined towards having a negative view of this technology. Finally, we could not evaluate from the survey performed whether the sample population who was not convinced with a once-through cycle base their opinions on an economical argumentation due to the over-costs that this management strategy implies.

5. Conclusions

The total cease of the Spanish nuclear centrals is an irreversible action, as it would not be economically feasible to open new ones afterwards. That is why it must be a strongly premeditated choice, with all the possible consequences very clear.

In the current European context, analyzing the position of France and Germany regarding nuclear energy and with this project, it has been proven that the nuclear technology is a key technology to maintain a stable electric system while reducing the emissions of greenhouse gases. Therefore, it seems highly advisable to keep the Spanish nuclear centrals operating, thus guaranteeing the electric supply 24/7 and helping achieve the goal of a decarbonized society without compromising the society.

The availability, stability and predictability that nuclear technology possesses, offers the possibility of an adequate management of the electric system.

6. References

[1] Bataille C, Waisman H, Colombier M, Segafredo L, Williams J. The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. Climate Policy. 2016;16(sup1): S1-S6.

[2] L. Rodríguez Penalonga, Modelo para la gestión sostenible del combustible nuclear gastado, 2020.

Master Thesis

The fourth *R* in nuclear technology - Reprocessing

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Abstract: With industrial revolution, carbonization began leading to the current greenhouse effect and global warming, one of the main issues in current society. Due to this emerging climate crisis, countries are trying to switch to a decarbonization system. Nuclear energy began in 1950s, constituting a powerful technology with no CO_2 emissions that could contribute to the decarbonization of the system without compromising the electrical supply and without economical caveats. However, the lack of experience regarding radioactive waste management and the two nuclear accidents in Chernobyl and Fukushima, have made nuclear energy to have a poor social acceptability and to be left out of the portfolio suggested by the European Union as environmentally sustainable technologies, despite the recommendation of experts. Thus, this project aims to analyze the current opinion of the Spanish population regarding nuclear energy as well as developing an economical analysis of the instauration of a twice-through cycle strategy. We observed that the younger population, more engaged with the environment, has a more positive opinion of nuclear energy. Furthermore, all surveyed population agreed on improving their opinion if a twice-through cycle strategy was in place. Despite being a more expensive strategy regarding direct costs, we found that it would be compensated by a higher energy production and lower indirect costs, making twice-through cycle a possible option. Therefore, this project sets the ground for a deeper technological consideration of nuclear energy as an asset for decarbonization and environmental sustainability.

Keywords: Nuclear energy; Reprocessing; Waste management; Twice-through of fuels; Environmental sustainability; Decarbonization; Social acceptability.

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1. Introduction

Due to the emerging climate crisis, the world needs to switch to a decarbonization society, which is not an analog of electrified society, as other energetic vectors could also contribute to the decarbonization of the system – take for instance hydrogen as an energetic system which is currently taking off thanks to the European investment into its research development. From a technical perspective, there are several technologies that would allow the decarbonization being one of those the nuclear technology as it allows production of energy without CO_2 emission [1]. Therefore, in order to achieve a complete decarbonization of the electric system minimizing the risks and associated costs, a varied portfolio of all options available is needed [2]. Excluding nuclear energy of this portfolio for the decarbonization of the system would increase the electric production notable **[¡Error! No se encuentra el origen de la referencia.]**. As well as diminishing the stability of the whole electrical network, which would then lead to supply cuts.

To tackle this crisis, the European Commission has launched the European Green Deal, which aims to make the 27 member states reduced their carbon emissions in 55% by 2030, turning into full climate-neutral by 2050 [4]. But in order to achieve these goals, it is necessary to invest in new sustainable projects that would replace the current energetic system. Thus, the European Union (EU) created a listing of what the Commission considers as environmentally sustainable activities, called the “EU taxonomy”, establishing six environmental objectives which includes: climate change mitigation (1) and adaptation (2), protection of water and marine resources (3), transition to a circular economy (4), pollution prevention and control (5) and protection of biodiversity and ecosystems (6). However, despite the favorable experts’ report about nuclear technology for the energy transition [5], nuclear energy was not included into this EU list of environmentally sustainable activities due to the lack of experience regarding radioactive waste management and spent nuclear fuel management. Therefore, an appropriate management of the radioactive waste, in a controlled and coordinated manner, would tip the scales for nuclear energy to get integrated into the EU Taxonomy and thus be considered an environmentally sustainable activity.

All industries generate waste, as this is an inherent action of the human being. In the last decades, the generation of different types of waste has increased alarmingly [6]. With the aim to protect the planet, the rule of the "3Rs" was proposed: *Reduce – Reuse – Recycle*. Additionally, in the last few years, a new R was included: *Recover*. This last process is directly linked to industrial processes and consist of recovering materials or elements that would then be used as raw materials. The reprocessing of used nuclear fuel refers to recover radioactive materials that are still useful for nuclear reactors. Thus, here we propose the *Reprocessing* as the "4th R" of nuclear technology.

Furthermore, there is a clear need for nuclear energy in Europe to achieve the European Green Deal and full climate-neutrality by 2050, as it would be impossible to maintain the energetic demand relying solely on the wind and solar technologies. For instance, Spain holds a diversified energetic mix, with 12% of total energy production being hydraulic and only 8% being solar energy [7]. The reason for solar energy to only account for a small percentage, being Spain one of the member states with the highest levels of solar radiance in EU, relies on the limitations of this technology [8]. Only wind production substantially contributed to energy production in Spain, accounting for 22% of the total production, in a similar level to nuclear energy production [7]. However, although wind energy production is equivalent to nuclear production, the power installed is significantly lower in the case of nuclear energy production -being 17093 MW of wind power versus 7117 MW of nuclear power [9] – thus making nuclear energy production far more efficient. Following this context, if Spain decided to continue with a denuclearization plan, the country would have to substitute that 22% of nuclear energy production for a new technology with a similar energy production yield and that is catalogued as environmentally sustainable in the EU Taxonomy. As previously stated, nuclear energy would constitute a perfectly environmentally sustainable activity if radioactive waste management were performed correctly.

Despite this, Spain decided to follow a once-through strategy, where the waste generated is directly stored without any treatment. The Spent Nuclear Fuel (SNF) management firstly thought to put in place in Spain was the reprocessing, when dismantling *Vandellós I*, thus sending the SNF from that nuclear plant to reprocessing plant of *La Hague* in France and *Sellafield* in United Kingdom. But the glasses from this reprocessing are still awaiting to be sent back to Spain from France. In the *VI Plan General de Residuos Radiactivos* from 2006, currently in place in Spain, a strategy for once-through cycle was established as well as the construction of a Centralized Interim Storage (CIS) to store the SNF from the different nuclear plant in Spain. This CIS was planned to be in place and running from 2010; however, its construction has not even been started due to all the difficulties encountered that continuously delay this project [10]. Without a working CIS, as soon as the nuclear plant's pools get filled, some Independent Spent Fuel Storage Installations (ISFSI) are built.

This waste management strategy has contributed to a poor public opinion of the nuclear energy industry in Spain, alongside the fear of nuclear accidents -such as those occurred in Chernobyl in 1986 and Fukushima in 2011-. The accident of Chernobyl in 1986 has been described as one of the worldwide events that caused important psychological damage to the entire population due to the uncertainty of the consequences and the ignorance about radiation effect in humans. Afterwards, the accident in Fukushima in 2011 led to the plan of different EU member states to dismantle all their nuclear plants, despite the fact that the Fukushima plant had a cold shutdown without any major human damage and all deaths were associated to the tsunami and not to the radioactivity. But importantly, alongside the worries about a possible nuclear accident, another matter that worries the public is the price of the electricity [11]. Nuclear energy not only gives stability to the energetic system but is able to reduce the electricity price as well, as it does not depend on external elements, making it a potential ally to the public.

In this project we have analyzed the current public opinion about nuclear energy in Spain and estimated the economic feasibility of the nuclear advanced reprocessing. We observed that the once-through cycle is not considered to be the best option even to the people that had a good impression of nuclear energy (64% agreed with an opened cycle versus the 71% of nuclear energy) as well as the twice-through cycle, or closed cycle, could reduce the negative opinion to nuclear energy significantly, which leads to the conclusion that an appropriate and efficient spent nuclear fuel (SNF) management would improve the public opinion of nuclear energy and contribute to the stabilization of this technology as one of the environmentally sustainable technologies used for worldwide transition to a climate-neutral society.

2. State of the Art

2.1. Nuclear Fuel cycle:

The nuclear fuel cycle encompasses all the stages and processes that are made on the uranium and its later derivatives, from its extraction in the mines until its final disposal. The different types of cycles define different strategies for the management of fissile nuclides residues thus assuming important implications of the management of nuclear residues and proliferation of nuclear weapons, both of them two of the three main negative impacts of nuclear power in the environment [12]; being the last one nuclear accident.

The nuclear fuel cycle has two main stages: front-end (initial phase) and back-end (management of the spent nuclear fuel). The front-end comprises all the stages precious to the usage of nuclear fuel in the central reactors for the generation of nuclear power. On the contrary, the back-end refers to all processes in which the spent nuclear fuel is involved, from its extraction from the reactor until its final storage.

2.1.1. *Front-end – from nature to reactor*:

This first phase has five stages: (1) mining to extract the uranium, (2) conversion of the concentrated uranium (U_3O_8) into uranium hexafluoride (UF_6), (3) enrichment of uranium to obtain the concentration of the fissionable isotope U-235 required by the nuclear reactors, (4) conversion of enriched UF6 into uranium dioxide dust (UO_2), and finally (5) the fabrication of fuel element.

To obtain the fuel element, the starting point is a uranium pill, obtained after compression of UO_2 into cylindrical tables, as it can be observed in **Figure 1**.

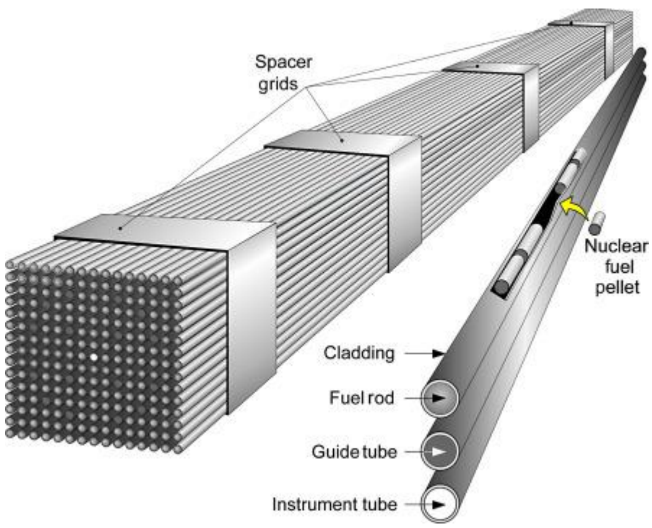

Figure 1. Fabrication of fuel element.

2.1.2. *Back-end – managing Spent Nuclear Fuels*:

The management of the Spent Nuclear Fuels (SNF) aims to avoid that such residues become a risk for the environment or the human beings, neither in a direct not indirect way through air, water or the food chain. This stage of the nuclear process starts with the extraction of used nuclear fuel form the reactor until the final disposal of such. The fuel is considered "spent" when the growth of the fission products, responsible of absorbing the neutrons, and the decrease of U-235 consumed in the reaction, reduce the efficacy of the fission reaction chain [13]. This reduction in the efficacy leads to the need of substituting part of these elements for a new fuel, what is denominated as a “re-charge”.

The SNF that is extracted still hold a high energetic capacity, as the reactor only uses 5% of the energy initially contained [13]. This remanent energetic capacity can be used again in other reactors.

The different stages of this phase depend on the SNF cycle strategy followed. There are currently two main cycle strategies available: once-through cycle (or *opened cycle*) and twice-through cycle (or *closed cycle*).

2.1.2.1 *Once-through cycle*:

This strategy consists of the direct storage of SNF, without any intermediate reaction of treatment. This storage is performed according to the safety guidelines in place for thousands of years, until the radioactivity of the SNF reaches the levels or natural uranium or safe levels. This cycle consists of two main phases: temporal storage and final storage, including the intermediate phases of transport and encapsulation.

There are two types of **temporal storage**, depending on the type of refrigeration needed: wet storage – using pools of cold water-, and dry storage – using an inert gas or just normal air as refrigeration. Firstly, after extracting the SNF from the reactors, it is introduced into pools inside the nuclear central with the goal of diminishing its radioactivity and using the remanent heat to easy the next phases. They are kept in these pools for 5 to 10 years, depending on the nuclear central characteristics (type of reactors, burnt degree…) [14]. This phase is shared between once-through cycle and twice-through cycle, being the very first phase of the temporal storage of SNF.

After being refrigerated in pools, the SNF is transported to a dry storage, where it will be kept for 50 to 100 years, until its final disposal at a proper depth. This storage could be placed either at the nuclear central (denominated *Independent Spent Fuel Storage Installations* or ISFSIs), or at an external localization where the SNF of different nuclear centrals is mixed (denominated *Centralized Interim Storage* or CIS). Finally, the radioactive residues are sent to their final destination, where they will be kept until the radioactivity levels are the same as natural uranium or safe levels. The most common option for this final storage is a *Deep Geological Repository* or DGR.

2.1.2.2 *Twice-through cycle*:

The SNF extracted from the reactors is composed mostly of uranium, bound to the fission products and minority actinoids. Despite the composition changes regarding the nuclear central characteristics and the reactor, the amount of uranium is around 95%, being thus the energetic capacity still very high. Therefore, the twice-through cycle separated the SNF into different components to be able to take advantage of such residual energetic capacity. Thus, the twice-through cycle of SNF is considered a resource and not a residue, a concept supported by the principles of circular economy which converts this strategy into one based in sustainability, notably reducing the quantity of residues and their temporal scope [15].

To reclaim these components with a high calorific content, it is needed to separate the fissional materials (uranium and plutonium) from the rest of components of the SNF. The uranium and plutonium extracted from it can be reused by forming a mix of uranium oxide (UO_2) and plutonium oxide (PuO_2), called *mixed oxides* or MOX. This fuel can be used in the nuclear centrals, thus achieving a better exploitation of the uranium. After being used in the reactors, MOX can be reprocessed again although it is not advisable to it more than twice or three times, as the reduction in the efficacy could be very high. The rest of the components of the SNF (fission products and minority actinoids) undergo a process of vitrification to reduce their radioactivity and to easy their manageability as well in later stages.

The reprocessing of nuclear residues is usually performed through a process denominated *PUREX*: Plutonium Uranium Recovery by EXtraction. This process, developed in United States in the last half of the 20th century, is the most used nowadays for reprocessing at industrial scale.

Amongst the countries that have PUREX reprocessing plants, the most important ones due to the volume of processed residues are the ones in Japan (Rokkasho), France (La Hague), United Kingdom (Sellafield) and Russia (Mayak).

Separating the uranium and plutonium from the rest of the components of SNF is considered a conventional twice-through cycle. However, there are novel technologies still under development that allow the separation of some of the fission products and minority actinoids. These technologies would thus be *advanced reprocessing technologies*.

2.2. *Reprocessing technologies*:

The reprocessing step consists of separating, via chemical reactions, the different materials that compose the SNF [16]. Currently, the conventional reprocessing only separates uranium and plutonium from the rest of the components. However, new technologies under development aim to achieve the separation of minority actinoids and fission products as well.

The SNF is mainly composed of reusable materials (approximately 95% is uranium) that keep their energetic potential after use. The need for developing better reprocessing technologies rely on them being economically feasible and is line with the current interest towards an environmentally sustainable future. Achieving a circular economy, where the produced "residues" could be reused thus becoming new resources and reducing the final volume of waste, is the aim of the advanced reprocessing. Only then the nuclear energy would become a really environmentally sustainable power, with no CO2 emission and a low rate of waste production, becoming the ideal ally for the decarbonization process.

It is worth noting that despite reprocessing would reduce the nuclear waste production, it would never eliminate them completely, and therefore final storages would still be needed for those products that cannot be reprocessed. There are several reprocessing technologies currently under development, but only PUREX is commercially available.

2.2.1. *Conventional reprocessing - PUREX*:

The current reprocessing available at large scale is PUREX. This technology was developed in the second half of the 20^{th} century thanks to the military technology and its experience. PUREX consists of breaking down the SNF, dissolving it in nitric acid and extracting the solvents by using tributilphosphate (TBP). With this process, the uranium and plutonium are separated from the fission products and minority actinoids, that remain dissolved in the acid.

To start the reprocessing, the SNF is transported to a reprocessing plant, where it is introduced in pools (wet storage) identical to the ones in the nuclear centrals. They can be kept in these pools for several decades until being reprocessed. Then, there are four phases in the PUREX process: (1) coating removal, (2) dissolution, (3) separation of uranium and plutonium, and (4) treatment and conditioning of radioactive residues [17].

2.2.1.1 *Coating removal*:

The fuel is coated with different metals in order not to get in contact with the refrigerant. Therefore, for the SNF to get in contact with the nitric acid and thus react, a coating removal step is needed. This removal could be mechanical or chemical.

2.2.1.2 *Dissolution*:

To separate the uranium and plutonium from the rest of components, the SNF is dissolved in nitric acid. The degree of dissolution depends on several factors such as temperature, porosity or plutonium concentration. This process leads to the emission of nitrogen oxides and volatile fission products that require a treatment before their release into the atmosphere.

2.2.1.3 *Separation and purification*:

To extract the uranium and plutonium, it is needed to filter the solution and regulate the pH until obtaining the optimum values for the separation. Once separated, the extracted uranium and plutonium undergo a chemical process to separate them from each other, and later they are purified.

2.2.1.4 *Treatment and conditioning of residues*:

The uranium and plutonium are reconverted into PuO_2 and UO_2, and they are sent to fuel manufacturing plants in order to get reused, while the fission products and minority actinoids that are kept in liquid form are vitrified and stored as highly radioactive residues but with a lower half-life than the residues obtained after a once-through cycle.

The PUREX reprocessing is a developed technology that achieves nearly 100% of separation of uranium and plutonium, and thus the improvement of reprocessing relies in the reduction of the radioactivity of the produced residues to ease their storage.

2.2.2. *Advanced reprocessing*:

At the beginning of the 90s, a new strategy of closed cycle emerged, based on the transmutation of certain radionuclides of a long half-life present in the SNF, with the aim of diminishing their radiotoxicity and thus reducing the time until they reach a safe level of radioactivity [14]. In order to perform the transmutation, a previous reprocessing step is needed to separate the minority actinoids (Np-237, Am-241 and Cm-242/243/244) and some of the fission products of long half-life (Tc-99 and I-129). Complementary, the interest to separate the Sr-90 as well and Cs-137 emerged, as they are heat transmitter and thus condition the design of DGRs. Although the separation of strontium and cesium is viable now, their transmutation is economically unfeasible nowadays.

Regarding the advanced reprocessing technologies, there are two main lines of research: hydrometallurgical processes –using wet medium-, and pyrometallurgical processes, developed in a dry medium.

2.2.2.1. *Hydrometallurgical processes*:

These processes take place in a wet environment and are based on the extraction of isotopes through organic solvents. These technologies are the most developed ones and take place from the PUREX method, including improvements in the yield of the process and reducing the toxicity of the reprocessing and volume of residues sent to a final storage. Amongst them we can find UREX, DIAMEX and TRUEX [18].

2.2.2.1.1 *UREX*:

The UREX process (*URaium EXtraction*), also known as advanced PUREX, is an adaptation of the PUREX process to extract neptunium, apart from uranium and plutonium, as well as other minority actinoids with high yield. One of the advantages of such technology is the possibility of extracting plutonium alongside other elements, reducing the amount of pure plutonium that can be extracted and thus diminishing the risk of proliferation. This process consists of putting the SNF through several consecutive phases of solvent extraction through dissolutions of nitric acid, separating different components on each of them. Depending on the different phases that are made and the actinoids that are meant to be extracted, there are several variants of this process.

2.2.2.1.2 *DIAMEX*:

The DIAMEX process (*DIAmide EXtraction*) is a solvent extraction process that allows to extract actinoids and lanthanoids from the residues generated through PUREX. This process, developed in France, consists of 16 phases divided into four main categories: extraction, incorporation of the SNF to an acid solution, two stages of depuration of the organic phase, and a final separation using nitric acid.

This technology has been highly developed and tested in laboratories, being almost ready to get incorporated at a commercial level.

2.2.2.1.3 *TRUEX*:

The TRUEX process (*TRansUranic EXtraction*) is also based in PUREX and presents itself as an alternative to the DIAMEX process, thanks to which the transuranic elements (plutonium, uranium, americium and curium) can be separated from the SNF, largely reducing the radioactivity of the residues [18].

This process was developed in United States at the end of the 20th century, and it is an extraction process through solvents that achieve the separation of the cited elements from the acid solution. This process has 20 different stages divided into 4 categories: extraction (where the SNF is incorporated to an acid solution), depuration from the organic phase (first of the americium and then of the plutonium), and several phases of solvent cleanse. This technology has already been tested in different laboratories giving very good results.

2.2.2.2. Pyro*metallurgical processes*:

These processes take place in a dry environment, involve several stages and are based on the extraction of isotopes through molten salts, such as chlorides or fluorides, or fused metals, such as cadmium, bismuth or aluminum [18]. This process is designed for fuels used in Generation IV reactors and instead of being applied to oxide fuels they are applied to metals.

Amongst the pyrometallurgical processes we can find the US electrorefining, the EU electrorefining and the liquid-liquid extraction.

2.2.2.2.1 *US electrorefining*:

In order to develop a process that was economically feasible, able to adapt to the variety of nuclear materials and weapons, and efficiently operable with minimum generation of residues, researcher from the Argonne National Laboratory (USA) developed a pyrochemical electrorefining process in 1991 designed to treat the IFR spent fuel. There are currently two different versions of electrorefining developed by American researchers from the Argonne National Laboratory (ANL), one that only recovers uranium (ready to be industrialized) and the other that allows the recovery of all transuranic elements as well (only tested at laboratory scale).

The process starts with the removal of fuel rods from the irradiated fuel assembly, to then being chopped into 6-7mm pieces. These segments are then placed into perforated steel baskets in an electrorefiner, which is the key point to separate the actinoids from the fission products present in the spent fuel. Then, the pure uranium is collected at a solid mandrel cathode and the mixture of plutonium, curium, neptunium, americium and some rare earth fission products at a liquid cadmium cathode. The remaining products stay in the salt and the cadmium layer below the salt.

2.2.2.2.2 *EU electrorefining*:

The EU process is designed to reprocess metal fuel through separation by electrorefining on an aluminum cathode in molted chloride. This process is based on the ANL one, and further developed by the European projects EUROPART and ACSEPT, and now the SACSESS project.

The advantage of the EU electrorefining process compared to the ANL one is that the prior reduction step is not needed, as it is based purely on electrolysis without any reductive salt/metal extraction step, and thus the process gets simplified. At the end of this process, the actinoids and uranium are separated and recovered.

2.2.2.2.3 *Liquid-liquid reductive extraction*:

This process, developed by the CEA Marcoule in France, aims to separate the actinoids from lanthanoids with LiF-AlF_3. To do so, in the liquid-liquid reduction extraction process the nuclear spent fuel is put through a thermal treatment of 1100ºC to remove cesium and rubidium, and later the elements remaining are undergo fluorination at 450-500ºC, removing the zirconium in the ZrF_4 form. Once these elements have been removed from the mix, the reductive extraction step takes place using molten fluoride salts.

3. Objectives

This project aims to determine the feasibility of the advanced reprocessing of spent nuclear fuel (SNF), using a strategy that would allow to reuse part of the nuclear fuel again, thus reducing the volume of final SNF disposed and improving the social acceptability of nuclear technology. This project aims to justify the need for Spain to keep the nuclear energy as part of its energetic mix, both for technical, environmental and economic reasons. Likewise, its aims to prove that there would be a good social acceptability of nuclear technology if the SNF management improves and switches to a close-cycle model, developed in line with the *4R*.

The specific objectives for this aim are two:

(1) To survey the current public opinion about nuclear energy in Spain and to evaluate the impact of a the twice-through cycle waste management system in the public opinion.

(2) To study the economic impact of reprocessing the spent nuclear fuel.

4. Materials and Methods (Methodology)

4.1. Economical model of reprocessing:

When choosing a certain strategy of spent nuclear fuel management, there are several factors to bear in mind. Amongst them we can find the social acceptability, environmental impact, technical aspects and finally, economical aspects. In this project, we analyzed the economic feasibility of an advanced twice-through cycle, being the economic viability a crucial aspect when choosing a national strategy.

The advanced reprocessing technologies that would allow to create a twice-through cycle strategy are still under further development. Despite the many advantages of this type of process, the associated cost of the implementation of such novel technologies to manage SNF is still not clear. There are several studies assuring that the cost of advanced reprocessing, depending on the isotopes in order to be separated for recycling –apart from uranium and plutonium-, would range between a 5% and 15% more expensive than the current reprocessing technologies. However, taking into account that the current reprocessing methods do not reuse the obtained materials outside the options of reusing uranium and plutonium, advanced reprocessing could constitute a more profitable option as new raw materials could be obtained from this process.

To analyze the economic feasibility of the advanced reprocessing, we estimated the increment in costs of the advanced process compared to the cost of conventional reprocessing. Such estimation was made from the data obtained in the PhD thesis of Laura Rodríguez [22]. The goal of such calculation was to demonstrate that an advance reprocessing could be a feasible option for the waste management in a near future, thus becoming part of the portfolio of possible strategies for Spain to improve SNF management.

4.1.1. *Mariño model*:

This model is developed to estimate the associated cost of different SNF management technologies through the Net Present Value (NPV) technique to then analyze the differences amongst the different scenarios. The calculation of costs is established as the calculation of the normalized costs through the definition of the sum of discount costs (cash flows) divided by the total production of electricity [22].

The model, developed in MATLAB, consists of four stages: (1) estimation of the future dates for reactor recharges and final SNF inventory, (2) calculation of the annual material flow, (3) calculation of costs, and (4) estimation of the future electricity production of the nuclear plants.

Finally, for each installation of SNF management, there are three established types of costs: investment, operational and maintenance, and dismantling. Alongside these ones, there will be an extra cost for the storage of nuclear containers in the pool, the cost of the containers themselves and the cost associated to the transport between the different installations.

4.1.2. *Considered hypothesis*:

When performing this study, we held the following hypothesis:

- There is no associated payment for the plutonium obtained
- There is an advanced reprocessing in which lanthanoids and actinoids are obtained as well, alongside plutonium and uranium
- The lanthanoids and actinoids obtained in the reprocessing would be considered as raw material that could be put on the market, thus obtaining an economical benefit from them.

4.2. Current public opinion surveys:

In order to assess the current opinion of the Spanish population regarding nuclear energy and its impact in the environment, a CAWI survey (Computer Assisted Web Interviewing) was designed with the five, below stated questions that could be answered in the scale from “excellent” to “very poor” or with a “yes/no” answer type.

Q1: What is your opinion about the nuclear energy?
Q2: Would your opinion improve if there were no associated nuclear waste disposal?
Q3: Would you agree with the nuclear waste to be indefinitely stored in safe and controlled underground casks?
Q4: Would your opinion improve if the nuclear waste were recycled instead of stored?
Q5: What is your age frame?

The survey was aimed at both men at women over 18 years old in Spain, being classified in three age groups: less than 30 years old, from 30 to 50 years old, and more than 50 years old. The survey was launched using the website *SurveyMonkey* (https://es.surveymonkey.com) and was available for a month.

We collected a total of 423 surveys, that were then analyzed and pondered in order to be representative of the current age groups in Spain, using the population data from the *Instituto Nacional de Estadística* (INE). See **Table 1** for further details.

Table 1. Survey technical characteristics.

Survey characteristics	Aims
Name of the project	Perception of the Nuclear Energy
Universe	Men and women over 18 years old in Spain
Objective	To analyze whether a twice-through management of the spent nuclear fuel would improve the current social acceptability, compared to the current social opinion
Sample type	Randomized
Date of the survey	Opened from 28/06/2021 until 21/07/2021
Size of the sample	We obtained 423 completed surveys, pondering the results in order to make them representative of the current age groups in Spain
Data collection method	CAWI survey (Computer Assisted Web Interviewing)

The surveyed population was divided into three age groups:

1) Below 30 years old: this group mainly collects engineering students from all academic levels and newly graduated students. Therefore, it is a population with a good intellectual formation and with capacity to understand the differences between once-through cycle and twice-through cycle (related to the questions performed). They are young people for who the use of technology to achieve an environmentally sustainable future.

2) Middle age group: between 30 and 50 years old: addressed to all type of people, not necessarily experts in technology but with certain formation. Therefore, they consist of active population with the capacity of changing their minds about their opinion regarding nuclear energy if enough technical improvements are given.

3) Above 50 years old: they represent more than half of the collected answers. This group is addressed to the general population, without identifying their formation level. Based on the contacts the survey was sent to, it is estimated that this group holds a high level of qualification, similar to what happens in the middle group.

5. Results

5.1. Economical study:

To perform the economic study, we used the results obtained from the Mariño model developed in the PhD thesis by Laura Rodríguez [22]. Starting from the sensitivity study (see **table 2**), we applied the hypothesis previously defined to obtain the results regarding the advanced reprocessing, which was not considered in such PhD thesis.

Table 2. Analysis of the sensitivity obtained from the Mariño model.

Cost	-50%	0%	50%
ISFSIs	12.793,45 M€	12.820,68 M€	12.847,90 M€
CIS	12.539,90 M€	12.820,68 M€	13.101,45 M€
DGR	12.648,65 M€	12.820,68 M€	12.992,70 M€
Transportation	12.476,93 M€	12.820,68 M€	13.164,42 M€
Casks	12.741,02 M€	12.820,68 M€	12.900,33 M€
Reprocessing	7.506,56 M€	12.820,68 M€	18.134,79 M€
Reprocessing Pu 0	5.735,19 M€	9.277,93 M€	12.820,68 M€

One of the simplifications taken into account in this project was to consider both reprocessed plutonium and uranium as raw materials that could be then put on the international energetic markets. It was not considered the possibility of having to grant a monetary compensation or other benefit in kind for other EU member state to keep the plutonium. Therefore, the cost corresponding to *Reprocessing Pu 0* from **Table 2** was the one taken. This current project studied the base case (0%) and the cases +50% and -50%, observing a lineal trend in the variation of the associated cost of reprocessing. Based on this linearity and starting from the base case corresponding to 9.277,93 M€ and the hairpin of over-costs from reprocessing obtained from previous studies in the literature, the cost of advanced reprocessing was analyzed as shown in **Table 3**.

5.1.3. *Analysis*:

From all the studies found in the literature, we obtained an over-costs estimation of the advanced reprocessing compared to the current reprocessing technologies that ranges from 5% to 15% of over-cost. Setting this as the starting point and taking into account the previously mentioned hypothesis, we obtained the over-cost and total cost of the advanced reprocessing for an increment of 5%, 10% and 15%. This increment is variable, due to the fact of this technology being commercial and thus depending on the negotiations taking place with the companies involved.

Table 3. Analysis of the advanced reprocessing cost compared to the current cost of reprocessing.

	0%	***5%***	***10%***	***15%***
Over-cost	-	354,27 M€	708,55 M€	1.062,82 M€
Total Cost	9.277,93 M€	9.632,21 M€	9.986,48 M€	10.340,75 M€

In order to be able to analyze the trend of the cost, we plotted the over-cost against the total cost, as it can be seen in **Figure 2**.

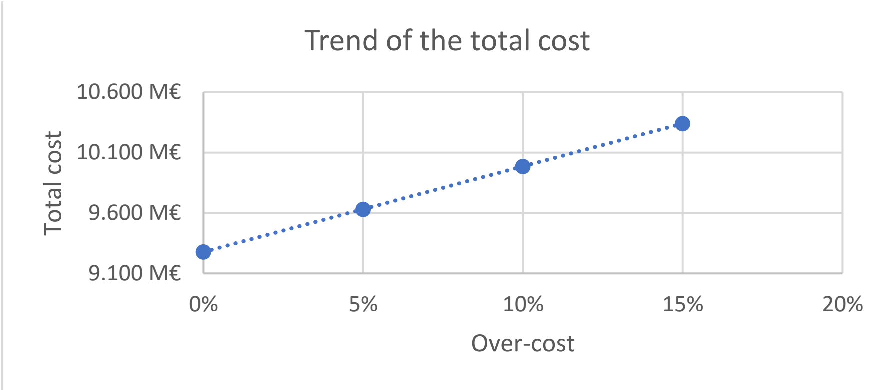

Figure 2. Linear trend of over-cost against total cost

Although this is an estimated cost, it is appropriate to bear in mind that this over-cost will largely be compensated with the sale of the recycled raw materials (sodium, fluor), as well as with the reduction of waste volume that return to the countries that sent their SNF to advanced reprocessing plants, the decline in the radioactivity of such SNF, and the reduced transport need derived from this decrement in waste volume. With the aim of analyzing the impact of these reduction into the associated costs of the different stages of SNF management, obtained thanks to the benefits of advanced reprocessing, we estimated these cost reductions as can be observed in **Table 4**.

Table 4. Analysis of cost reductions in the different stages of SNF management.

	ATC	***AGP***	***Transport***
Cost Reduction	3%	1%	1%

5.2. <u>Social acceptability</u>:

We analyzed the answers of the first 4 questions rating different aspects of the public perception about nuclear energy and used the last question to set it under the appropriate age frame for ponderation.

5.2.1. *Opinion about the nuclear energy*:

We grouped all opinions in Table 2. As it can be observed, over 70% of the population has a positive perception of the nuclear energy and only 5% (even below the number of “indifferent” answers) had a very poor perception of it, as can be seen in **Figure 3** below. We considered as positive answers “excellent” and “good”, while negative answers were assigned to “poor” and “very poor”.

Table 5. Answers from Q1 “what is your opinion about the nuclear energy”.

Options	**Answers (%)**	**Answers (n)**
Excellent	26%	109
Good	45%	189
Poor	17%	74
Very poor	5%	20
Indifferent	7%	31
	100%	**423**
	Not answered:	0

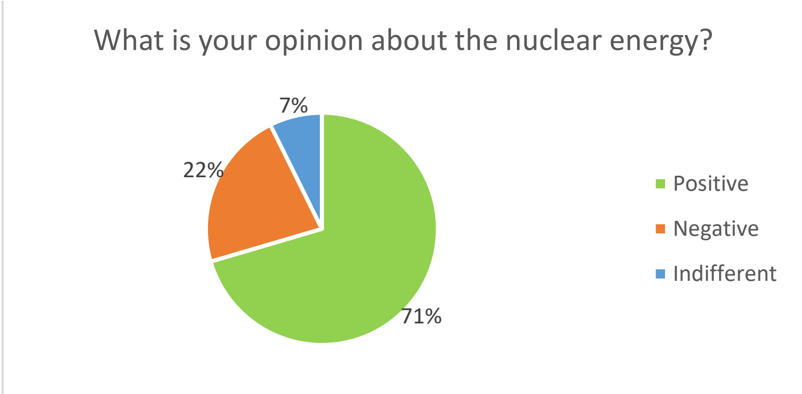

Figure 3. Percentage of positive and negative answers regarding the nuclear energy

5.2.2. *Would your opinion improve if there were no associated nuclear waste disposal?*

We grouped all opinions in Table 6. As it can be observed from both **Table 3** and **Figure 4**, over 90% of the population would have a better perception of the nuclear technology if there were no nuclear waste disposal associated to it, which shows the concerns of the population regarding nuclear waste and their effect on health and environment.

Table 6. Answers from Q2 "would your opinion improve if there were no associated nuclear waste disposal".

Options	Answers (%)	Answers (n)
Yes	91%	384
No	9%	39
	100%	**423**
	Not answer:	0

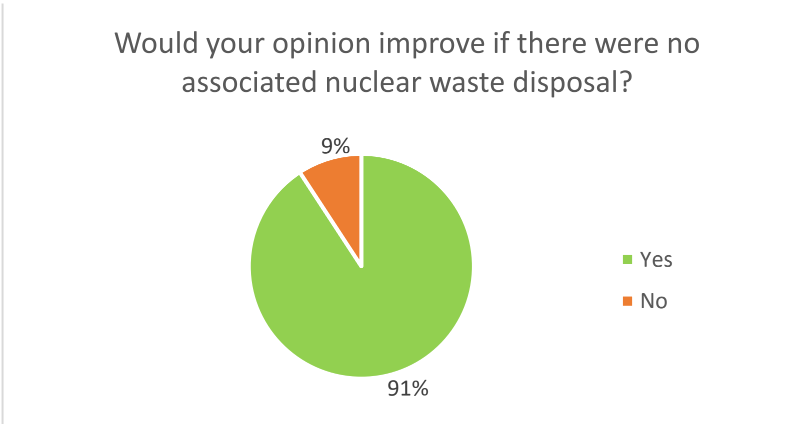

Figure 4. Percentage of yes/no answers regarding an improvement in nuclear energy perception without waste disposal

5.2.3. *Would you agree with the nuclear waste to be indefinitely stored in safe and controlled underground casks?*

We grouped all opinions for this question in **Table 7**, showing that the shifting to twice-through would not be an inconvenient for most of the surveyed population, thus being this a possible alternative to the current nuclear waste management in terms of social acceptability.

Table 7. Answers from Q3 "Would you agree with the nuclear waste to be indefinitely stored in safe and controlled underground casks?".

Options	Answers (%)	Answers (n)
Yes	64%	269
No	36%	151
	100%	**420**
	Not answered:	3

5.2.4. *Would your opinion improve if the nuclear waste were recycled instead of stored?*

We grouped all opinions for this question in **Table 8**. It can be observed that the vast majority of the population (93% of positive answers vs 7% of negative ones) would have a more positive perception of nuclear technology if there was a recycling process of the nuclear waste instead of the currently in place storage of them. Therefore, linked to the previous question (see table 4 for details) a twice-through management of nuclear technology waste would be largely accepted into the Spanish society.

Table 8. Answers from Q4 "Would your opinion improve if the nuclear waste were recycled instead of stored?".

Options	Answers (%)	Answers (n)
Yes	93%	392
No	7%	29
	100%	**421**
	Not answered:	2

5.2.5. *What is your age frame?*

In order to contextualize the answers into age frame and ponder them, we asked the subjects to say their age range (less than 30, between 30 and 50, and over 50 years old). **Table 9** collects the number and percentage of subjects from each age group and Figure 5 shows the subjects distributed in "students" and "workers", considering those in the age frame below 30 years old as students and all the rest as workers. This estimation was based in the sample population that the survey was sent to.

Table 9. Answers from Q5 "*What is your age frame?"*

Options	Answers (%)	Answers (n)
Less than 30 years old	27%	113
Between 30 - 50 years old	27%	114
Over 50 years old	46%	196
	100%	**423**
	Not answered:	0

6. Discussion

For a better interpretation and discussion of the results obtained regarding the public opinion of nuclear energy, the age quotas were taken into account, thus turning the results obtained in our survey representative to the current population by age. To do so, we obtained the numbers of inhabitants on each age frame through the *Instituto Nacional de Estadística* (INE)'s database and we pondered the proportions obtained in the surveys with the age quota obtained through the INE. This ponderation can be seen in **Table 10** for further details.

Table 10. Ponderation of results according to INE age quota

Age	INE Population	Surveyed population	Ponderation	Equivalent surveyed population
18-29	5.879.514	113	0,56	64
30-49	13.757.32	114	1,30	149
>50	19.505.01	196	1,08	211
TOTAL	39.141.84	423	1,00	424

Once the pondering was made, we analyzed the answers to all questions made by age group and represented them in **Figures 5-14**.

The answers to the question 1, regarding the perception of nuclear energy, were plotted showing the different answers by the different age groups (see **Figure 5**). In addition to this, it can be observed in **Figure 6-8** the percentage of positive, negative or indifferent perception of nuclear energy depending on the age. It can be observed that, regarding perception of nuclear energy, both the population under 30 years old and above 50 years old had similar opinions, while the middle age group (from 30 to 50 years old) had a more negative perception of nuclear technology. The fact that this age group has a worse opinion of nuclear compared to the other groups could be because they belong to the active population that is more engaged with the current environmental issues and therefore, they believe that nuclear technology needs to still improve its waste management in order to be fully environmentally sustainable.

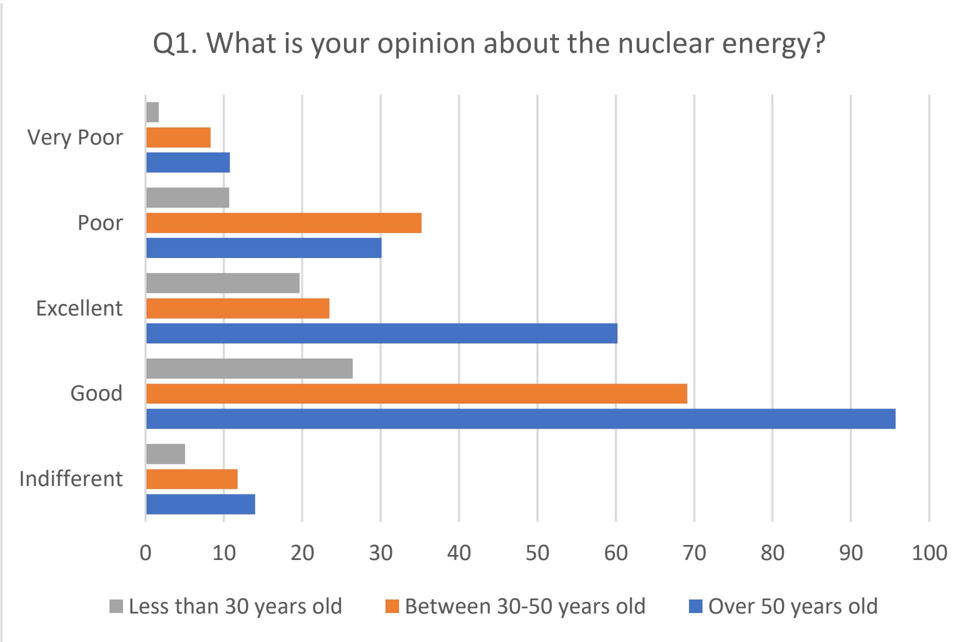

Figure 5: Answers to Q1 grouped by age.

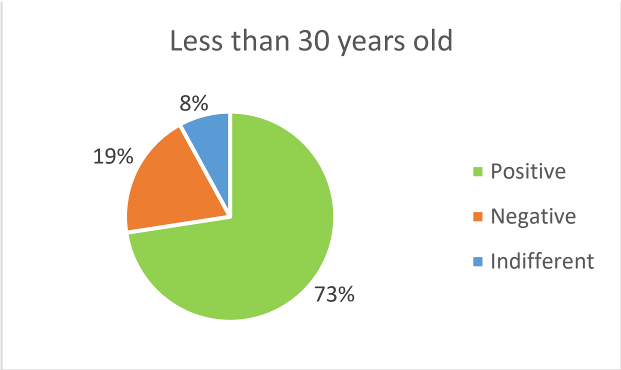

Figure 6: Positive/negative perception based on Q1 in the population below 30 years old.

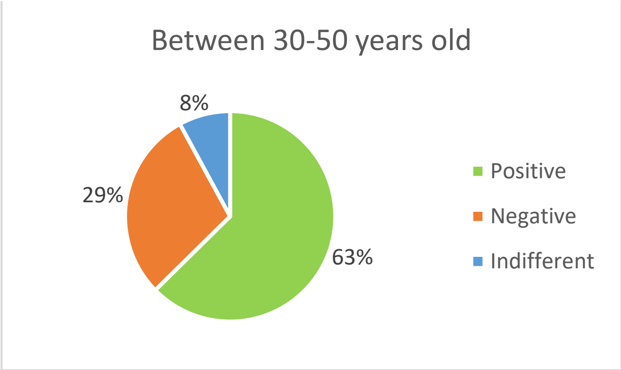

Figure 7: Positive/negative perception based on Q1 in the population between 30 and 50 years old.

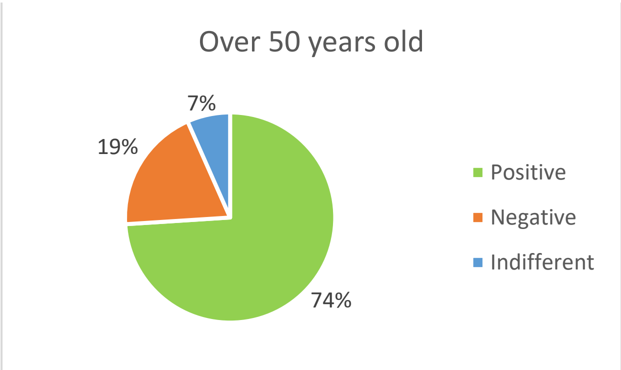

Figure 8: Positive/negative perception based on Q1 in the population above 50 years old.

When analyzing whether or not their opinion would improve if there were no associated nuclear waste disposal, it was observed that that the answers were similar across age groups. To corroborate this observation, plots were made for each age group, noticing identical percentages between the two first groups (below 30 and middle group), as shown in **Figures 10** and **11**. However, the percentage of people stating that their opinion would not change even without nuclear waste production was double for people over 50 years old, as seen on **Figure 12**. Being this group the elderly one, we believe that their opinion regarding nuclear technology, being this a positive or a negative opinion, it already deeply rooted and thus would remain unchanged, while the younger population is more prone to accept that an improvement of the technology would lead them to improve their opinion about nuclear energy. This could also be due to the fact that the term “closed cycle” and environmental sustainability is a relatively novel concept that has had a greater impact on the youngest, conscious that they are the ones to lead the change towards a more environmentally sustainable future.

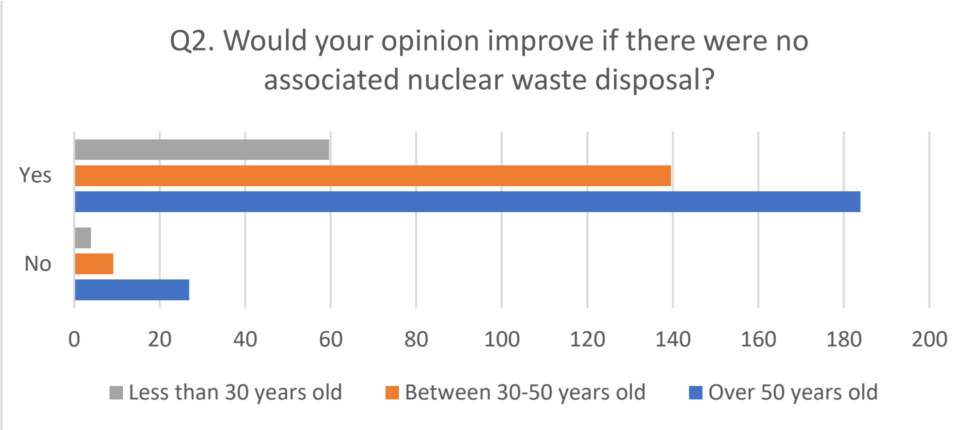

Figure 9: answers to Q2 classified by age groups.

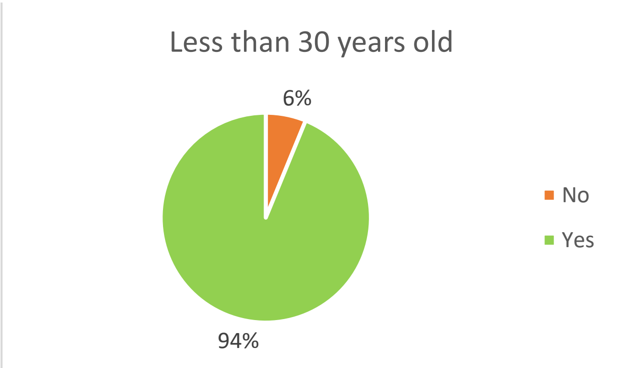

Figure 10: answers to Q2 of the population below 30 years old.

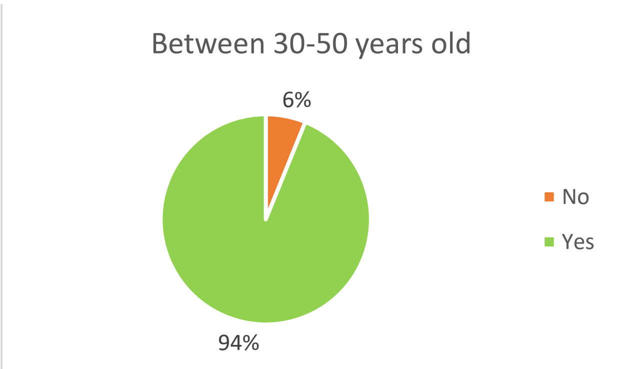

Figure 11: answers to Q2 of the middle age population.

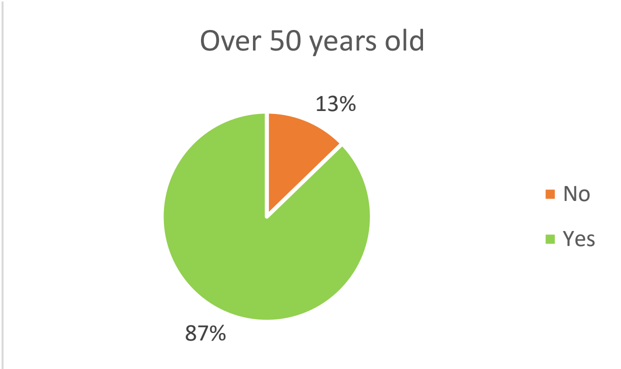

Figure 12: answers to Q2 of the population above 50 years old.

The next question was referring to the public opinion towards the nuclear waste management as a once-through cycle. In order to ask this in an indirect manner, we referred to the final storage of the waste, always under the established control measures. **Figure 13** collects all given answers divided by age group, showing that most of them, nearly 60%, would have a positive answer.

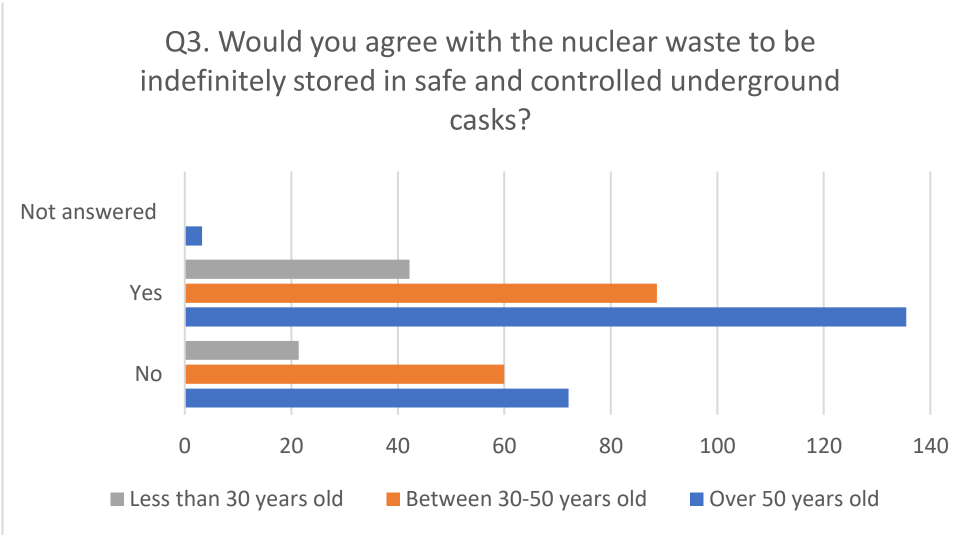

Figure 13: answers to Q3 classified by age groups.

Finally, we indirectly asked about their opinion regarding a twice-through cycle management strategy by referring to the recycling of the residues produced. **Figure 14** represents the positive and negative answers of all age groups, and it can be observed that a vast majority of nearly 92-93% of the population would have a better perception of nuclear energy if the waste products were recycled instead of just stored as it occurs with the current once-through cycle. These results fully support the affirmation of several studies that propose waste management in nuclear energy as one of the main issues.

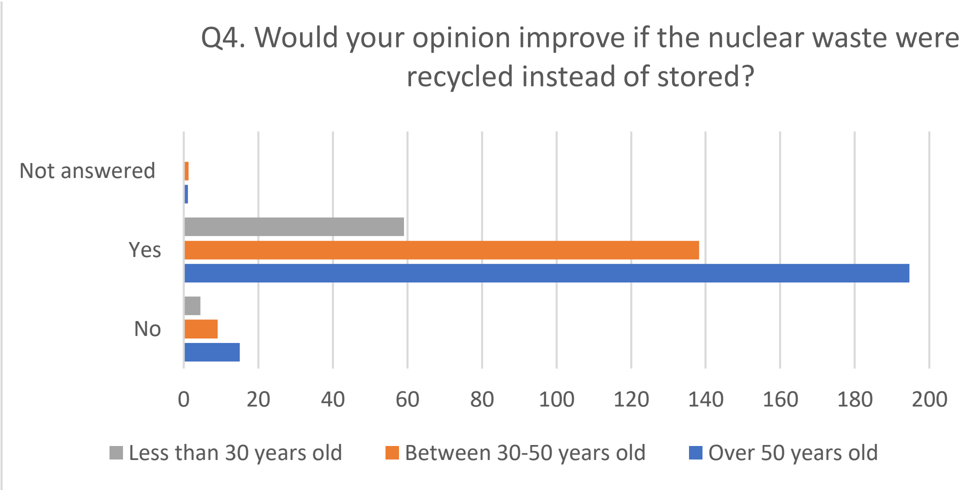

Figure 14: answers to Q4 classified by age groups.

7. Conclusions

The total cease of the Spanish nuclear centrals is an irreversible action, as it would not be economically feasible to open new ones afterwards. That is why it must be a strongly premeditated choice, with all the possible consequences very clear. Despite Europe is nowadays divided regarding the nuclear energy topic, there are two of the main member states that have positioned themselves with a final strategy: France and Germany. On the one hand, Germany has opted for closing all its nuclear reactors, reaching this goal at the end of 2022 and basing the electric network system in renewable energy and gas centrals, although keeping several coil centrals. This country defends that there should be an integration of the European electric network in order not to lose stability. On the other hand, France is considered the reference country for energy exportation in the European Union and bases its energetic mix in the nuclear technology, being this type of energy responsible for the 77% of the electricity production of the country. France assures that it will keep nuclear energy as the base of its energetic mix for the next decades as the best strategy for reaching a decarbonized society, because the closure of such centrals would lead to the need of opening new coil and gas centrals and importing energy from coil, which at the end would not help achieving a total decarbonization of the electric system.

It has been demonstrated that the nuclear technology is the energy power that more hours of electricity produce, due to the fact that it only needs some breaks for recharge, and it emits zero greenhouse effect gasses. All this makes it a highly recommendable technology to maintain and thus keeping the Spanish nuclear central operating would ensure the electric supply 24/7, helping achieve the challenge of transforming into a decarbonized society without compromising the power supply. The availability, stability and predictability that nuclear technology possesses, offers the possibility of an adequate management of the electric system.

Based on all the answers collected, it is clear that a once-through cycle is not good enough for the population, not even for those who already hold a positive view of nuclear power (71% of population has a positive view of nuclear energy, while 64% agrees with the direct storage of SNF).

On the other hand, it was also observed that the usage of a twice-through cycle as SNF management strategy would significantly reduce the negative perception of the surveyed sample. This affirmation is held on the basis that 22% of the population answered to have a negative perception of nuclear energy and only 7% of them declared that a change of the SNF management strategy would not be enough for them to improve their opinion about nuclear. It is worth noting that inside that 7% who would not change their opinion, 5% had a “very poor” view of nuclear technology, which leads to the hypothesis that such opposition is funded upon ideological fundaments rather than technological knowledge. Following this line, only the 2% of the people below 30 years old declared to have a “very poor” opinion about nuclear technology, and this, linked to the fact that most people belonging to this sample group are engineering students, leads to the hypothesis that when having the grounds and knowledge about what is nuclear technology and how it works, people is less inclined towards having a negative view of this technology. Finally, we could not evaluate from the survey performed whether the sample population who was not convinced with a once-through cycle base their opinions on an economical argumentation due to the over-costs that this management strategy implies.

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Data Availability Statement: Data obtained from this study will be safely kept for a minimum of 3 years in the internal digital storage of the authors. The raw data will be available upon request to the authors.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A: Alignement of thi project with the Sustainable Development Goals (SDG)

A sustainable development is the one able to satisfy the current needs without compromising the possibilities of future generations. With this in mind, the United Nations defined the 17 Sustainable Development Goals (SDGs), that target three different aspects: social, environmental and economic [25].

This project is directly related to the environmental field and inside all the SDGs related to it, is mostly aligned with the ***SDG-13: Climate action – Take urgent action to combat climate change and its impacts***. This SDG aims to incorporate measures against the climate change at a national level to improve the mitigation of the global warming. In line with this, our project proposes the need of stablishing a strategy for the radioactive residues management in Spain, and poses the nuclear energy as a technology able to produce energy without greenhouse gas emissions, thus helping mitigate the climate change.

Another of the SDG related to this project is the ***SDG-7: Affordable and clean energy – ensure access to affordable, reliable, sustainable and modern energy for all***. The nuclear energy generates each year nearly 60.000 GWh, which is more than 20% of the whole amount of electricity consumed in Spain, therefore setting itself as the main power source free of CO_2 emissions. Furthermore, the electric production in nuclear centrals guarantees the electric supply 24/7 all year around and they operate in base, giving stability to the electric network. Finally, they do not produce greenhouse gas emissions, which makes it a key power source to obtain energy in an accessible manner and in an environmentally sustainable way, generating a high value for society.

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