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Synthesis report on predisposal LCA studies

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Abstract

This report describes the overall approach and work undertaken for the integration of life cycle assessment into the PREDIS project. The primary motivation for this work was to embed environmental sustainability into the development of the new predisposal processes under investigation in the PREDIS technical work packages. As these technologies are still being developed, there is an opportunity to both explore their potential and to direct further research and development in a way that leads to the most beneficial environmental outcomes. A secondary motivation was to enable the embedding of life cycle sustainability tools into nuclear back-end research and development activities more generally.

The life cycle studies performed in the PREDIS project have successfully demonstrated the value that can be added to research, development and demonstration programmes and raised the awareness of these techniques across the sector.

Keywords

Predisposal, Radioactive Waste Management, Decommissioning, Life Cycle Assessment, LCA

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1 Executive summary

This report describes the overall approach and work undertaken for the integration of life cycle assessment into the PREDIS project. The primary motivation for this work was to embed environmental sustainability into the development of the new predisposal processes under investigation in the PREDIS technical work packages. As these technologies are still being developed, there is an opportunity to both explore their potential and to direct further research and development in a way that leads to the most beneficial environmental outcomes. A secondary motivation was to enable the embedding of life cycle sustainability tools into nuclear back-end research and development activities more generally.

To achieve these goals, Task 2.5 'Cross work package strategic assessment' developed a protocol for life cycle assessment (LCA) and costing (LCC) including engagement of technical work package personnel to ensure agreement on how data would be collected and treated (see sections 2.1 and 2.2). A similar process of iterative engagement with partners was undertaken to define case studies for further investigation (section 2.3) leading to more detailed LCA/LCC of the following:

- **WP4** — decontamination of contaminated stainless steel surfaces via chemical oxidation reduction, and via decontamination gels (see Section 3)
- **WP5** — encapsulation of pump oils and scintillation cocktails using geopolymers (see Section 4)
- **WP6** — incineration of organic solids and ion exchange resins followed by geopolymer encapsulation and other containment techniques (see Section 5)
- **WP7** — SiLiF and SciFi monitoring systems for automated monitoring of waste stores (see Section 6)

At the time of writing, the modelling and results presented in this report for the above case studies are being broadened, finalised and submitted for publication in scientific journals throughout 2024 and 2025 as a series of 6-8 research papers by the authors of this report (Clayton, Kirk, Banford, Stamford). Readers are directed to these forthcoming articles for the most complete representation of the PREDIS LCA/LCC work. The first of these articles has been published, reviewing the current state of LCA implementation within nuclear back-end processes and helping to establish the case for wider adoption [1].

Throughout PREDIS, initial LCA/LCC findings have been used to improve and direct technology development via collaboration with partners. One such example includes the COREMIX-HP process in which climate change impacts have been decreased by 45% and costs by 13% as detailed in the forthcoming paper Clayton et al., *Environmental and Economic Assessment of the Application of an Optimised Chemical Decontamination Method on the Internal Surface of a Nuclear Steam Generator*.

In addition to the above case studies and their corresponding publications, multiple varied exercises were undertaken to maximise impact and to work towards the secondary goal of embedding life cycle sustainability tools within the nuclear sector:

1. Public LCA/LCC webinar, online, March 2023. Presentations were provided by The University of Manchester, CEA, Galson Sciences and VTT, and breakout rooms focused on decision-making and areas of interest to end-users.
2. LCA/LCC workshop, Manchester, May 2024. Open to PREDIS and EURAD partners, the workshop provided taught content and hands-on practical exposure to 2 LCA software packages as well as advanced training on LCA and LCC fundamentals.

3. Conference presentation and paper, IAEA, Vienna, November 2023. Kirk et al. "Applying a life cycle environmental perspective to the development of radioactive waste treatment technologies", in *International Conference on the Safety of Radioactive Waste Management, Decommissioning, Environmental Protection and Remediation: Ensuring Safety and Enabling Sustainability*.
4. Session chairing, poster presentation and PREDIS-EURAD exhibition hosting, NEA, Busan, May 2024. Rachael Clayton. *Seventh International Conference on Geological Repositories (ICGR-7): Empowering Progress in Developing Deep Geological Repositories.*

The structure of this report provides further details on the protocol, data gathering and case study selection process (section 2) and the specific application of LCA and LCC within each work package (sections 3-6).

2 Introduction

Life cycle assessment (LCA) and life cycle costing (LCC) have been integrated within the PREDIS project by the inclusion of an agreed assessment protocol, consistent interaction and iteration with project partners, and selection and analysis of specific case studies spanning the four technical work packages (WP4-7). This report details this process, beginning with the assessment protocol, data gathering activities and the process by which case studies were selected alongside 'base cases' which act to contextualise the results (see Section 1). Subsequently, the details and results of each case study are provided sequentially for each technical work package (Sections 3-6). Finally, the way in which this work relates to the Strategic Research Agenda (SRA) is discussed in Section 7.

2.1 Protocol for LCA/LCC

A public-access LCA/LCC protocol was published in August 2021 as Milestone M2.1 within Task 2.5 ''Cross work package strategic assessment of WP2 'Strategic Implementation'. The purpose of the protocol was to establish an agreed-upon approach such that all partners in PREDIS were familiar with the aims and approaches of the LCA/LCC work.

2.1.1 Key principles

LCA is an environmental sustainability tool that applies life cycle thinking in order to assess the consequences of human activities. Broadly speaking, LCA involves:

1. quantification of environmental burdens of a product, process or activity via assessment of the energy and materials used and wastes released to the environment;

2. quantification of environmental impacts (i.e. translating the above burdens into potential impacts); and

3. identification of opportunities for environmental improvements along the life cycle via the identification of 'hot spots'.

LCA is a well-established technique with a wealth of existing literature demonstrating its use. It is standardised via ISO 14040 and 14044 [2, 3], in which four key phases are identified, as outlined in *Figure 1*.

The first key principle of the PREDIS LCA/LCC protocol was that it would align with ISO 14040/44.

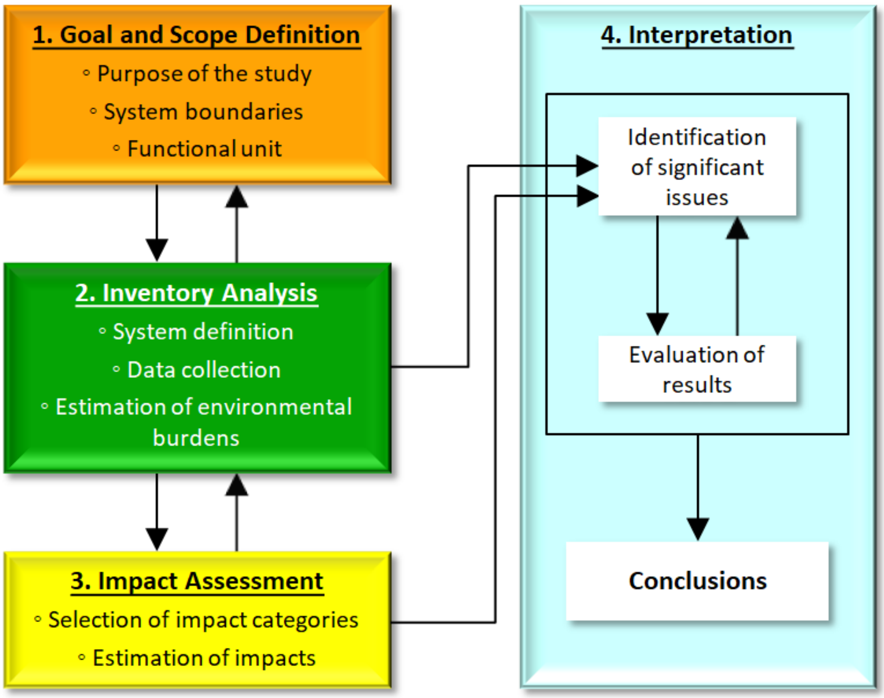

Figure 1 The four phases of life cycle assessment as defined in ISO 14044

As outlined in the figure, the Goal and Scope Definition phase involves defining the purpose of the study, the system boundaries and the functional unit.

The protocol established that:

1. The default goal and scope in PREDIS would be cradle to grave, starting at the receipt of waste to be treated (from waste generator organisations) and ending at final geological disposal (typically with a waste management organisation); and

2. The functional unit would be defined on a case-by-case basis, based on the specific technologies and scopes of each work package.

The Inventory Analysis phase of LCA is concerned with the collection of technical data, such as the mass and energy flows throughout the system's life cycle, and the estimation of flows to, and from, the environment. Typically, this is achieved with some reliance on existing databases or literature to provide data for background systems (e.g. data on the environmental burdens associated with material inputs). The protocol established that PREDIS would use Ecoinvent database [4] for background inventory data where preferable data do not exist, while technical specifications of the pre-disposal techniques under study will come from project partners.

The third phase of LCA, Impact Assessment, uses environmental impact coefficients, often referred to as characterisation factors, to estimate the potential environmental impacts caused by the burdens identified during the Inventory Analysis phase. The protocol defined the ReCiPe impact assessment method [5, 6] as the default option in PREDIS, on the basis that it is one of the state-of-the-art methods in current use and that some evidence suggests it is the most widely used method, although a plurality is evident in the community [7]. The protocol also established that information on all included impact categories would be disclosed wherever possible to avoid unconscious omission of important environmental impacts. Consequently, the environmental impact categories shown in Table 1 can be explored:

Table 1 Impact categories of the ReCiPe impact assessment methodology, adopted in the PREDIS protocol

IMPACT CATEGORY	ABBREVIATION
Climate change, default, excl biogenic carbon [kg CO2 eq.]	CC
Climate change, incl biogenic carbon [kg CO2 eq.]	CCb
Fine Particulate Matter Formation [kg PM2.5 eq.]	PMF
Fossil depletion [kg oil eq.]	FD
Freshwater Consumption [m3]	FC
Freshwater ecotoxicity [kg 1,4 DB eq.]	FET
Freshwater Eutrophication [kg P eq.]	FE
Human toxicity, cancer [kg 1,4-DB eq.]	HTc
Human toxicity, non-cancer [kg 1,4-DB eq.]	HTnc
Ionizing Radiation [kBq Co-60 eq. to air]	IR
Land use [Annual crop eq.·y]	LU
Marine ecotoxicity [kg 1,4-DB eq.]	MET
Marine Eutrophication [kg N eq.]	ME
Metal depletion [kg Cu eq.]	MD
Photochemical Ozone Formation, Ecosystems [kg NOx eq.]	POFe
Photochemical Ozone Formation, Human Health [kg NOx eq.]	POFh
Stratospheric Ozone Depletion [kg CFC-11 eq.]	SOD
Terrestrial Acidification [kg SO2 eq.]	TA
Terrestrial ecotoxicity [kg 1,4-DB eq.]	TET

In cases of multi-output systems, the protocol established that allocation would be tackled using system expansion, with other allocation approaches investigated as part of sensitivity analysis.

On life cycle costing (LCC), the protocol stated that:

- LCC models within PREDIS would align with their corresponding LCA models in terms of system boundary, system specification and functional unit, to maintain internal consistency.
- The choice of LCC metrics would be determined on a case-by-case basis, based on the specific technologies and scopes of each work package.
- Cost data would be sourced and estimated by researchers in Task 2.5 and in collaboration with technical work packages 4-7 wherever possible.

2.2 Data gathering

An LCA model can be separated into 'foreground' and 'background' systems, as outlined below (Figure 2). The PREDIS partners were asked for information on the foreground system only.

2.2.1 The 'foreground' system

The foreground system of an LCA model is the actual system and technologies under study. This may be described by a process diagram by engineers/scientists working on the system. In the context of PREDIS, it could include, for instance, the materials required to produce geopolymers and the processes undertaken to apply them to waste streams. Information on these systems For the foreground system, PREDIS LCA/LCC work relied primarily on information from project partners.

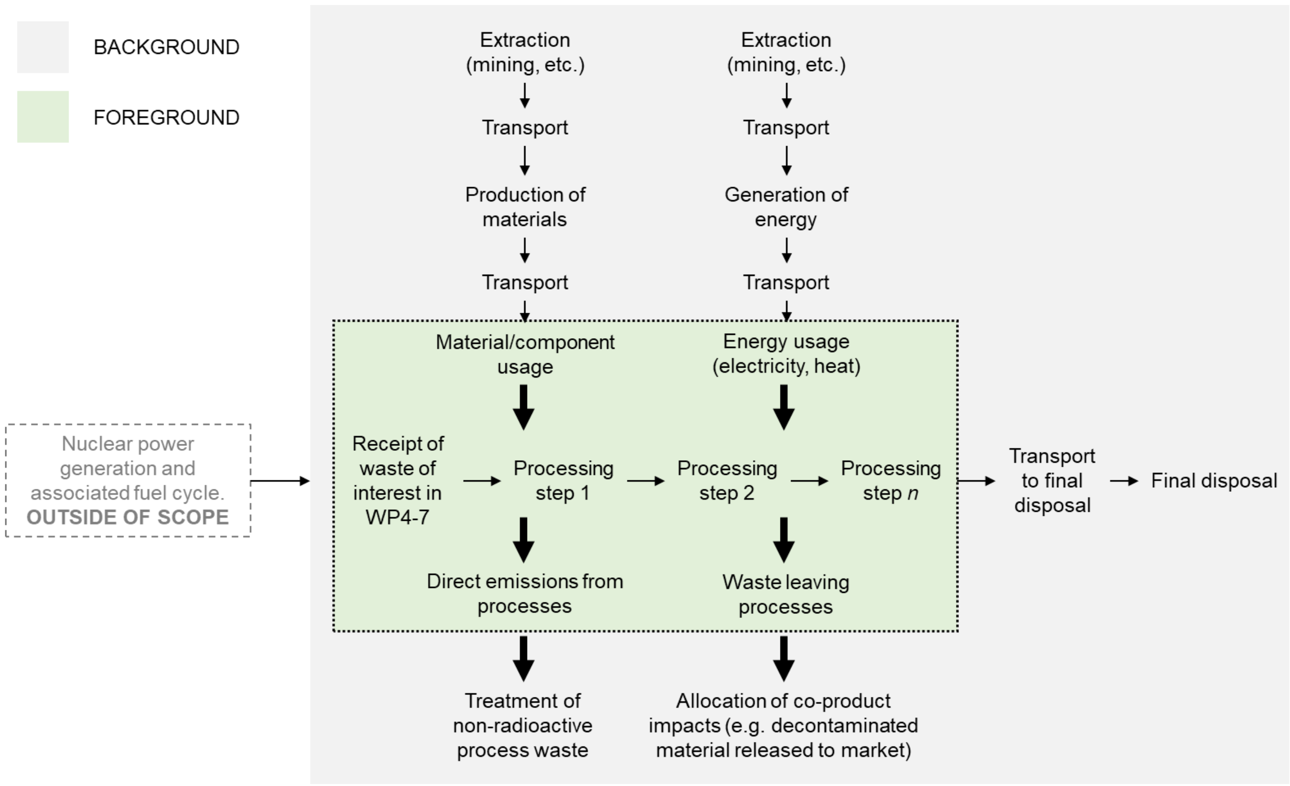

Figure 2 System foreground and background

To collect the necessary foreground data, a standardised yet flexible approach was taken. It was made clear that process flow diagrams and similar information could contribute to the LCA work, but a formal data collection template was also developed in Excel and circulated to partners. This was done iteratively via online meetings and email, with the resulting data collated by Galson Science Ltd and shared with The University of Manchester.

Partners were not expected to be able to complete every part of the data collection template and were encouraged to provide indicative values, ranges, and explanatory comments.

As the timelines and technologies of interest were different for each WP, a 'base case' would be agreed upon to outline the treatment of wastes without PREDIS pre-disposal approaches, and then to progress to several viable scenarios for different PREDIS pre-disposal case studies to be developed continuously according to the differing progression timelines of each WP. See Section 2.3 for detail.

2.2.2 The 'background' system

The background system describes flows of materials/energy that are secondary to the foreground system. For instance, the mining of minerals for geopolymer production, the extraction of metal ores and the production of components required to incorporate waste streams into geopolymers. Such data was sourced by Task 2.5 LCA practitioners from databases and literature, requiring minimal or no input from PREDIS project partners.

2.3 Selection of case studies and base cases

A series of meetings, both online and during in-person PREDIS annual meetings, was held throughout 2021 and 2022 to define the case studies and their associated base case treatment methods. Work package leaders and task leaders were present on each occasion, and their expertise was drawn upon to identify the best candidate technologies for study, based upon a)

applicability of the technique to the largest range or volumes of waste across Europe, and b) perceived level of interest from industrial and research partners.
The selected techniques were as follows:

- **WP4** — decontamination of a contaminated stainless steel surfaces via chemical oxidation reduction, and via decontamination gels (see Section 3)
- **WP5** — encapsulation of pump oils and scintillation cocktails using geopolymers (see Section 4)
- **WP6** — incineration of organic solids and ion exchange resins followed by geopolymer encapsulation and other containment techniques (see Section 5)
- **WP7** — SiLiF and SciFi monitoring systems for automated monitoring of waste stores (see Section 6)

The following sections detail each of these case studies in turn.

3 Work package 4 – Metallic waste

Work package 4 'Innovations in metallic treatment and conditioning' focuses on developing, optimising, and implementing techniques for treating radioactively contaminated metals. Part of assessing the feasibility of the treatment technologies includes robust life cycle assessments. In this report the optimisation of two technologies within PREDIS has been considered:

- An optimised chemical oxidation reduction using nitric permanganate and oxalic acid mixture with hydrogen peroxide treatment and precipitation (COREMIX-HP) process, as a chemical-based decontamination technique for use on the internal surface of steam generators.

- Optimisation of a decontamination gel for use on large planar surfaces such as hot cells.

Both technologies aim to reduce the overall volume of waste consigned to final disposal solutions across Europe and internationally by treating the irradiated surface leaving the larger volume of material free for recycle or reduced waste categorisation.

3.1 COREMIX-HP treatment

COREMIX-HP [8] is a technique being optimised in WP4 of the PREDIS project at Subatech, IMT Atlantique. COREMIX-HP is a chemical decontamination method utilising oxidation and reduction applicable to various irradiated metallic surfaces of a nuclear facility. In this study we have concentrated on the decontamination of stainless steel for which various versions of chemical decontamination methods have been developed such as HP/CORD-UV [9]. The COREMIX-HP process can be broken down into three distinct steps, COREMIX which is the oxidation reduction stage utilising nitric permanganate and oxalic acid, COREMIX-H which also incorporates a hydrogen peroxide treatment step to destroy any remaining oxalic acid and finally COREMIX-HP which further adds a precipitation step to separate solid metal hydroxides from the mixture making a solid waste suitable for encapsulation.

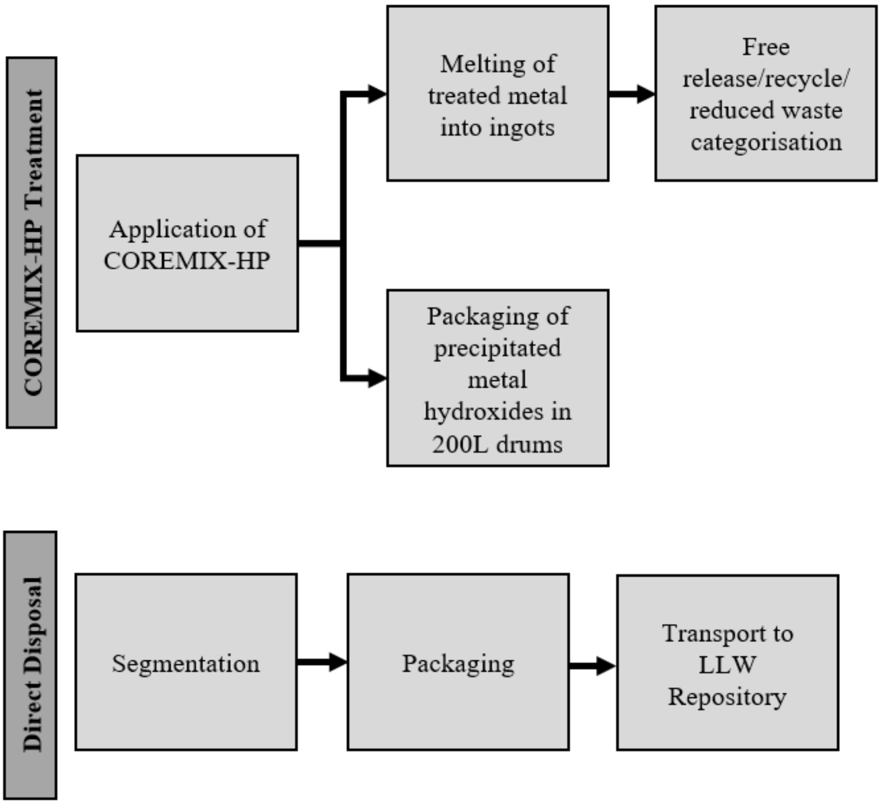

Figure 3: Steam generator treatment options considered in this study using COREMIX-HP

This case study has accounted for decontamination, conditioning and packaging of the solid radioactive waste produced by the process and the melting and recycling of the remaining mass of decontaminated metal ready for recycle as outlined in Figure 3.

This case study considers the treatment of a 900MW Mitsubishi steam generator used in French EDF pressurised water reactors using both COREMIX-HP and makes comparisons to direct disposal methods (Figure 3). Using literature from [10] the internal surface area of the steam generator tubes which can be decontaminated using COREMIX-HP during operation is calculated as ~4700m2. A value of 300t for the overall weight of a 900MWe steam generator was retrieved from literature detailing the design and construction of the main PWR reactor components [11]. The metal hydroxides produced are packaged in 500L stainless steel drums and grouted using a loading factor of 30% by weight [12].

The base case for this study is disposal of a steam generator in a low-level waste repository post operation. This involves the cutting, packaging and transport to an LLWR. An arbitrary distance of 100km from plant to LLWR was used, which is a standard practice in LCA where more generic modelling is required. As the PREDIS project considers waste producers across Europe and has interested parties beyond, it was considered suitable to make the transport distance a less specific value as it is likely to vary largely among these stakeholders.

Currently the COREMIX-HP process being developed in PREDIS is at lab scale, therefore it is important to note that, beyond larger capacity equipment, the upscaling of this process has not considered technique changes that would occur if this was implemented in industry such as reuse of reagents or specialised equipment.

The functional unit was 'the treatment of one steam generator'. The system boundaries were gate-to-gate, starting after cutting and removal activities with the steam generator ready for transport and ending with the free release/recycle/disposal of the treated steam generator material.

Full life cycle inventory data is provided in milestone MS16 and will be included in forthcoming publications by the authors.

3.2 Gel treatment

The use of gels for decontamination is being researched within WP4 of the PREDIS project by CEA, France [13]. The gels contain a corrosive solution which dissolves the surface layer of contaminated materials causing the contaminants to be incorporated within the gel. These gels are generally applied using a sprayer, left to dry, and then vacuumed off the surface. The final waste form is then the vacuum cleaner drum containing the dried gel residue, and the remaining material is available for recycling.

This case study has assessed the treatment of hot cell internal cladding with a surface area of 163m^2 based on the dimensions of an existing hot cell [14]. The thickness of the cladding is assumed as 480mm based on generic specifications [15]. Based on the density of stainless steel 316 the mass of metal requiring treatment is 625.9t or 78.24m^3.

The base case for this study is the removal, packaging and disposal at an LLWR of the stainless-steel internal cladding of a hot cell. The disposal route considered is based on a UKRWI waste stream report for LLW from the post irradiation examination cave at Sellafield [16] and the waste packaging is a half-height IP-2 ISO freight container with a capacity of 17m^3 [17].

The functional unit is 'the treatment of one hot cell'. The system boundaries are gate-to-gate, starting at the hot cell, post-operation, ready for decommissioning and ending with the disposal/recycle of the treated hot cell cladding.

Full life cycle inventory data is provided in milestone MS16 and will be included in forthcoming publications by the authors.

3.3 Results

3.3.1 COREMIX-HP

To decontaminate a steam generator made of AISI SS316 using 3 cycles of the COREMIX-HP treatment produces 856.7t CO2 eq. whereas sending a steam generator directly to disposal in low-level waste landfill is 229t CO2 eq. System expansion was completed in this study to further explore the impacts as, without this, the 'do nothing/the least' (direct disposal) approach will always appear to be less impactful. Without context this could lead us to the conclusion that we should not consider new approaches, however the impact of sending recyclable materials to irretrievable disposal cannot be ignored. Therefore, for these results the direct disposal option was also burdened with the impacts associated with producing 300t of virgin steel which would be required to replace that which was disposed of. After treatment with COREMIX-HP it was assumed the remaining steel would be suitable for reuse to some degree. Manufacturing 300t of steel produces 1407.8t CO2 eq. and when added to direct disposal, the overall impact is 1636.4t CO2 eq. which is over 1.9 times more environmentally damaging than using COREMIX-HP and preparing the liberated metal for reuse.

When broken down, the climate change potential of the different stages are as follows, COREMIX-H 792t CO2 eq. (92.4%), COREMIX-HP precipitation step 8.5t CO2 eq. (1%), recycling of treated metal including transport to facility and melting 53t CO2 eq. (6.3%), packaging of the waste metal hydroxides produced and transport to a disposal facility 2.9t CO2 eq. (0.3%).

As the initial 2-step COREMIX-H and additional precipitation stage in COREMIX-HP are being developed in PREDIS these were analysed further in Figure 4 and Figure 5.

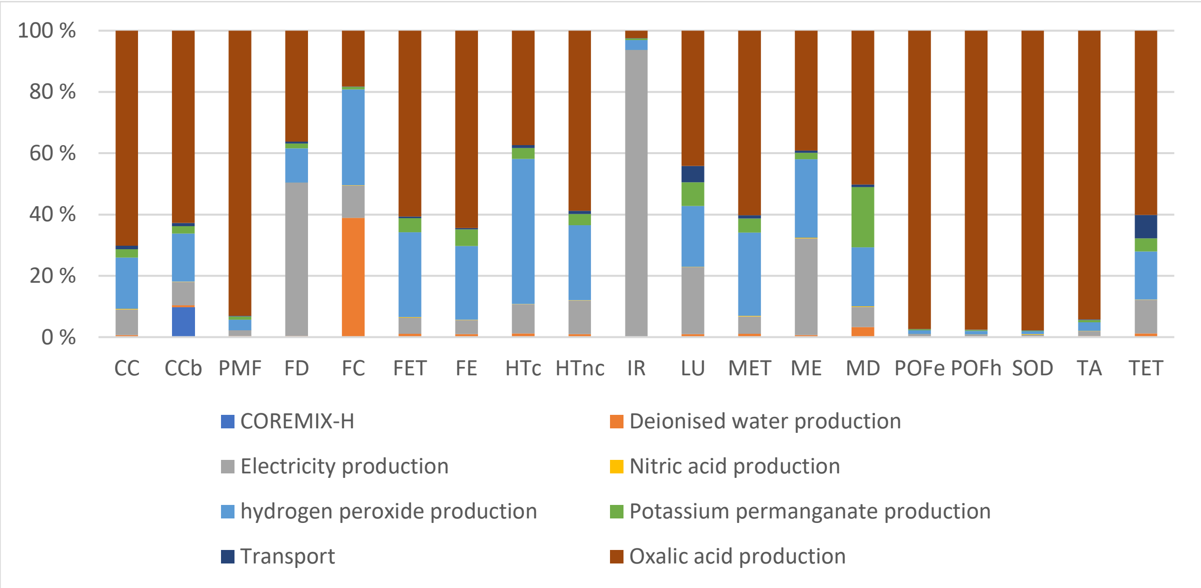

Figure 4: Impacts of the COREMIX-H process

Overall the majority of impacts in the COREMIX-H stage are from the production of oxalic acid, hydrogen peroxide and the energy requirements of the process. The impacts of oxalic acid are due to the large volume (1880m^3) required during decontamination, it is produced through propylene which requires large volumes of nitric acid, high heat and the use of propylene which is generally fossil-based. Although hydrogen peroxide is considered a green chemical and less is required than oxalic acid, it is produced through the anthraquinone process which is energy intensive and produces a large amounts of CO_2 causing its high impact to many categories. The large energy requirements come from the need to heat the solution during each cycle of decontamination for 6 hours, followed by 48 hours of heating to destroy any remaining oxalic acid.

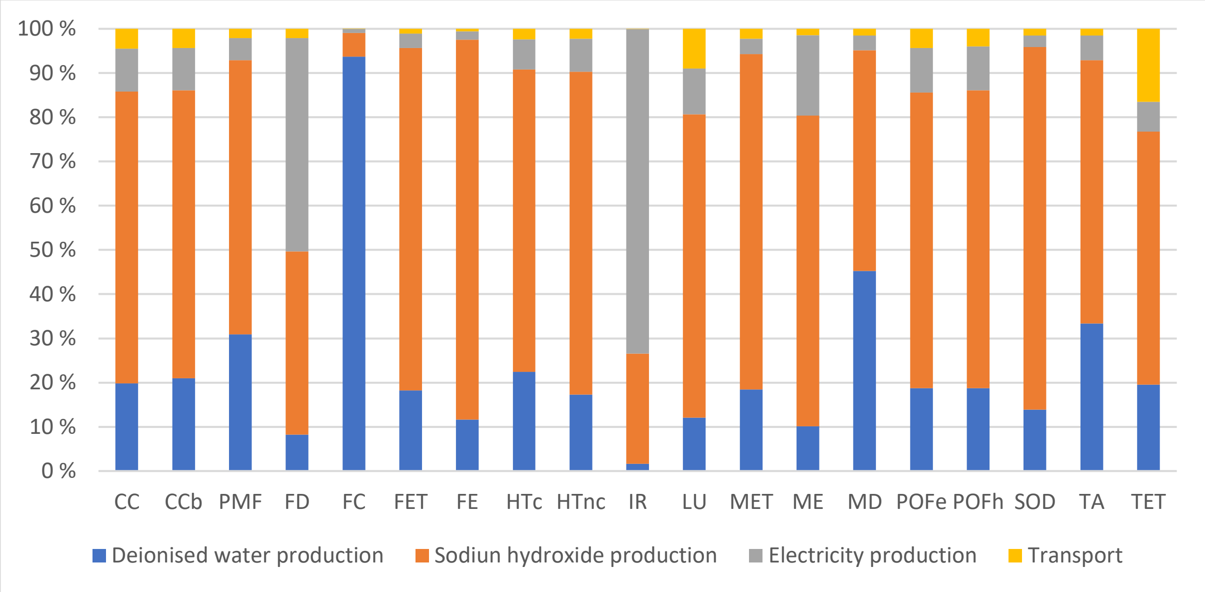

Figure 5: Impacts of the precipitation stage of COREMIX-HP

Impacts from the precipitation stage of the COREMIX-HP process are mostly influenced by sodium hydroxide, this is due to the energy intensive process of production. The only impact not dominated by the production of hydrogen peroxide is freshwater depletion, which is driven by the production of deionised water as would be expected.

3.3.2 Gel decontamination

The overall impact of treating a hot cell with dimensions of 163m^2 is 0.656kg CO2 eq. or 0.0035kg CO2 eq per m^2. When recycled the impacts increase to 105.3t CO2, or 0.646t CO2 eq. per m2 due to the energy required for production of ingots in an induction furnace ready for free release on the market. In comparison, the impacts of direct disposal of the hot cell cladding is 79t CO2 eq. or 0.48t CO2 eq. per m2. When burdening the direct disposal system with the impacts of producing the volume of metal that is not available for recycle once disposed, this increases to 3366t CO2 eq. or 20.65t CO2 eq. per m2. Therefore, with the currently formulation and application process, treatment using gel decontamination followed by the production of ingots suitable for free release produces only 3% of the CO2 eq. compared to the direct disposal and production of new steel.

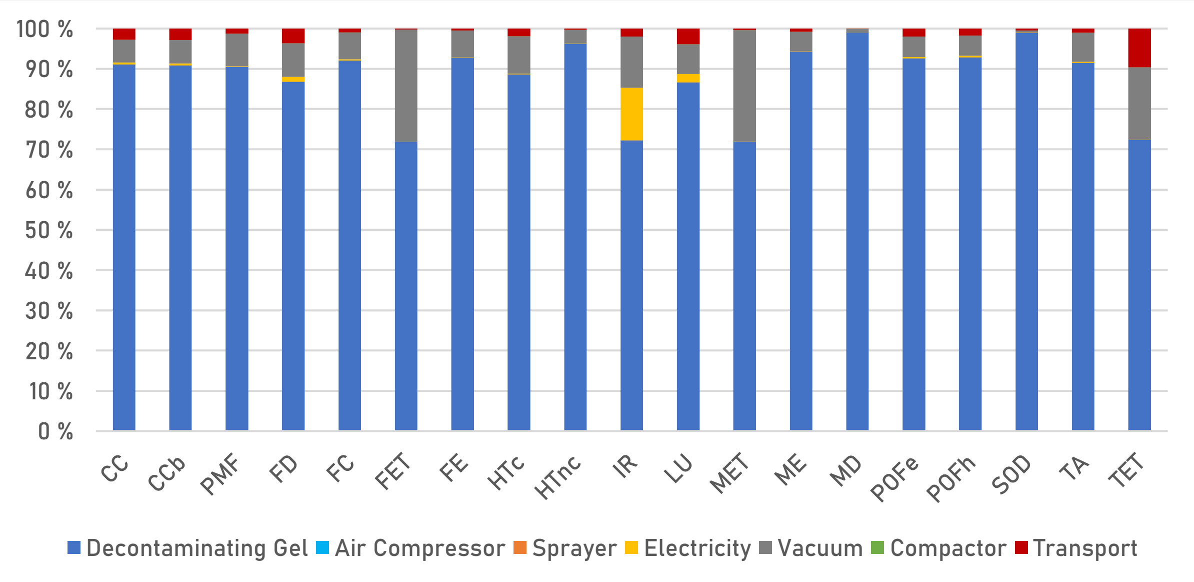

Figure 6: Impacts of using gel decontamination on a hot cell

As can be seen in Figure 6, the largest contributor to all impact categories is the production of the decontaminating gel itself. This was explored further as visible in Figure 7, with an average of 82.6% of impacts associated with the production of cerium nitrate, this is due to the intense process of obtaining cerium oxide from bastnaesite ore. Alongside the energy intensive step of mining, extraction of cerium oxide involves multiple stages requiring heat and the addition of chemical reagents.

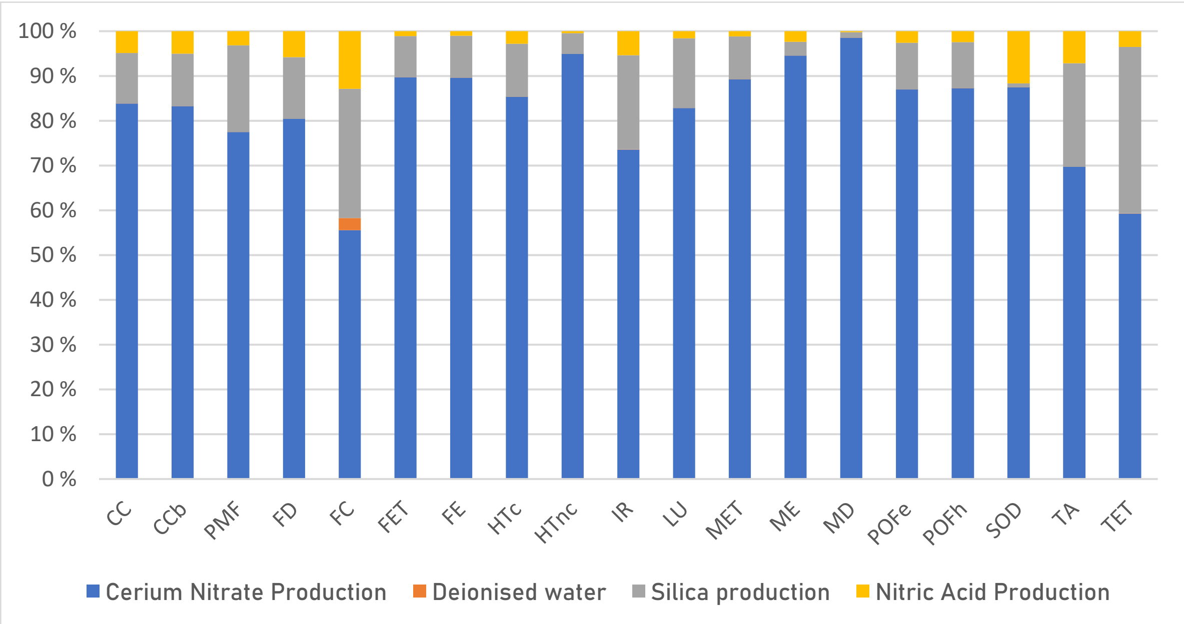

Figure 7: Impacts of producing the decontaminating gel

3.4 Conclusions

Currently the impacts of the COREMIX-HP treatment are dominated by the 2-step COREMIX-H process. The hotspots are attributed mainly to the use of the large volumes of oxalic acid and hydrogen peroxide. Further optimisation would be beneficial including research into reduction/reuse of reagents. Although this study has only considered the environmental impacts, it is important to consider other factors. This study has not considered, for example, the potential positive impacts due to reduction in volume of material sent to final disposal options or the impact of removing operational and safety considerations that are attributed to the transport of large radioactive structures (as COREMIX-HP can be applied in-situ), which are important considerations in decision making.

The decontamination gel treatment impacts are dominated by gel production, specifically the use of cerium nitrate and any further optimisation would benefit from the reduction of its use from an environmental point of view.

It is important to note that although the results have been provided in m^2 for both treatment options it would be incorrect to directly compare them as their applications are so different. COREMIX-HP is used in complex geometries where a gel could not be easily applied, whereas decontaminating gel can treat vertical metallic surfaces through prolonged contact. These treatment options are in development which means approaches evolve and data changes, future comparisons once treatments have been optimised further would be beneficial to realise the positive impact of implementing LCA at an early stage.

4 Work package 5 – Liquid organic waste

Data collection for the life cycle assessment of the treatment of radioactive liquid organic wastes was conducted by Galson Sciences Ltd. in which members of work package 5 'Innovations in liquid organic waste treatment and conditioning' were consulted as to the key processes being developed. From the survey a total of 13 scenarios (some consisting of sub-scenarios) were collected from 8 different partner organisations.

The breakdown of waste types being treated is shown in Table 2 by scenario and sub-scenario:

Table 2: Breakdown of waste categorisation from data collection

Waste Type	Oils	Scintillation Cocktails	Organic Solvent Mixtures	Decontamination Liquids	Misc.
Percentage	41%	23%	23%	4%	9%

Resultantly, it was determined that due to the high proportion of processes being developed as well as relatively simple chemical and physical properties, it would be prudent to solely consider oily waste as the primary waste of consideration for this LCA model. Oils in this regard reference contaminated process oils such as those arising from transfer pumps as well as lubricants and hydraulic fluids.

The breakdown of waste treatment types being developed is shown in Table 3 by scenario and sub-scenario:

Table 3: Breakdown of waste treatment methods from GSL data collection

Waste Treatment Method	Cement Encapsulation	Geopolymer Encapsulation
Percentage	38%	62%

Due to the binary consideration of waste treatment technologies within Work Package 5 as per the data collected, it was deemed important to consider both cement encapsulation as well as geopolymer encapsulation in the LCA model.

Beyond the scope of data collection, it is essential within the process of a comparative LCA to develop a baseline against which the scenarios are compared against. Through discussions with Work Package 5 members at the 2023 PREDIS Annual Meeting in Mechelen [18], Belgium a baseline of thermal treatment of the radioactive liquid organic waste was to be modelled. To further establish this baseline scenario, an assumption has been made that all the waste would be treated at the Centraco [19] radioactive waste treatment plant at the Marcoul nuclear site. This was selected due to the robustly understood nature of the incineration process at this facility for the treatment of radioactive liquid wastes as well as the high throughput capacity of 3,000 t/y. An average distance to the Centraco site was calculated using road transport by lorry as the primary method of delivery of the unconditioned waste. This would allow for a generic baseline to be developed which considers waste arising from various civil sources across the nation. The distance for the baseline transit therefore has been calculated by taking a weighted average of the distance between a given reactor site in France against the MWe output of said plant. This equates to ~620 km.

Due to the relatively small volumes of waste being considered it was considered that it would be best practice to consider that for the sake of modelling, the processes would all occur in the same EU nation, that being the highest producer of RLOW, France.

The overall goal of this study was to identify the life cycle environmental impacts associated with the treatment of contaminated pump oils through initial thermal treatment, encapsulation in cement and, alternatively, encapsulation in geopolymers to provide insights relevant to the strategic research agenda of waste management organisations in Europe.

The functional unit is the processing of 1kg of a_{avg} = 3E-05 GBq/kg b/g contaminated pump oil, and the system boundary is from the receipt of the unprocessed waste to the handoff of a conditioned waste package to the operator of a geological disposal facility.

Full life cycle inventory data is provided in milestone MS16 and will be included in forthcoming publications by the authors.

4.1 Results

The results for the LCA conducted are outlined in Figure 8 with climate change potential indicating that there is a significant change in environmental impact (kg CO2eq.) when comparing novel waste treatment technologies against the baseline of thermal treatment. Thermal treatment of 1kg of RLOW waste has a climate change potential of 3.24 kg CO2 eq. An increase in climate change potential can be identified through the use of in-situ emulsification and cementation of RLOW which equates to 5.07 kg CO2 eq. A significant decrease can be achieved through the use of geopolymer encapsulation with an estimated climate change potential of 1.79 kg CO2 eq.

In almost all categories, incineration of RLOW is favoured, likely due to the inclusion of off-gas treatment within the scope of the LCA which reduces direct emissions to the environment. This is compared to the use of cementitious matrices which result in direct emission of gaseous wastes. Due to the mix of specialist chemicals required for the encapsulation of RLOW in geopolymers increase can be seen, relative to cementation, in categories such as marine ecotoxicity and freshwater ecotoxicity because of mining and chemical production activities.

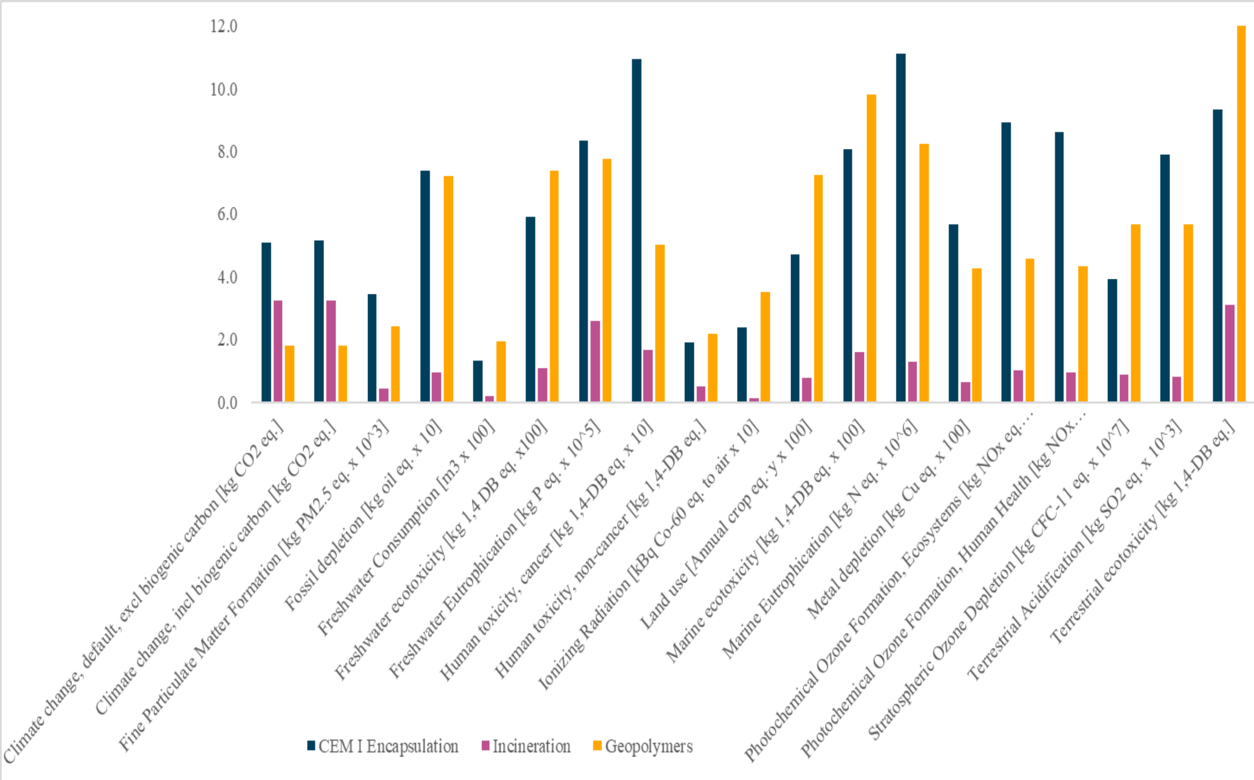

Figure 8: Life cycle environmental impacts of incineration, cementation and geopolymer encapsulation

4.2 Conclusions

It can be concluded from this LCA that a significant reduction in environmental impacts can be achieved through the utilisation of geopolymer encapsulation as opposed to cementation and thermal treatment (~2.8x and ~1.8x respectively) when climate change potential is concerned. In other impact categories, due to the nature of the facility, incineration showcases that as well as the reduction in volume contributing to a lower material use and therefore reduced impact, the inclusion of off-gas treatment such as DeNOx and wet scrubbing have significant impacts contributing to negligible impacts as opposed to the alternative scenarios.

Hot spots have been identified in other models such as potassium hydroxide usage in geopolymer encapsulation and Portland cement production and use in cement encapsulation. With the use of alternative, more sustainable materials, further reductions in climate change potential and other impact categories could be achieved. This should be the focus of research as regards these individual technologies.

Overall, the result of this LCA demonstrates that there should be a greater level of research focus on geopolymer encapsulation and similar technologies to reduce the overall impacts of the treatment of RLOW. This is due to the significant reduction in climate change potential by comparison to the other models, but consideration should be made at the material selection stage to reduce impacts in other categories.

5 Work package 6 – Solid organic waste

Data collection for the life cycle assessment of the treatment of radioactive solid organic waste (RSOW) was conducted by Galson Sciences Ltd in which members of work package 6 'Innovations in solid organic waste treatment and conditioning' were consulted as to the key processes being developed. As a result of the exercise, 4 key technologies were identified for consideration within the life-cycle assessment. The overarching IRIS process being developed by CEA enables size reduction of RSOW to the form of an ash which can then be further treated via other methods being developed. These are as follows:

- Hot Isostatic Pressing – University of Sheffield
- Encapsulation in volcanic tuff based geopolymers – Politecnico di Milano
- Compaction – CEA

As a result of the already concise treatment method data being gathered, all the above were therefore modelled within the LCA as outlined in the simple block diagram in Figure 9.

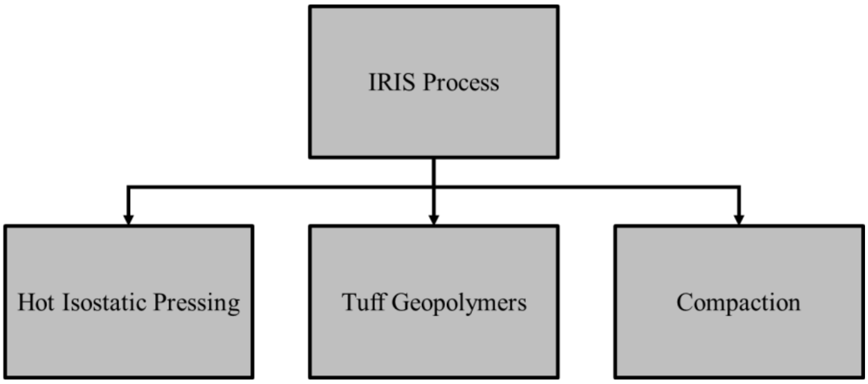

Figure 9: A simple process flow diagram outlining the scenarios being investigated in this LCA.

Beyond the scope of data collection, it is essential within the process of a comparative LCA to develop a baseline against which the scenarios are compared against. The baseline considers that the original thermal treatment process is not happening and therefore is modelled as the compaction of the waste surrogate, it also considers that the above processes are taking place at a 'generic' waste treatment facility which is of an assumed average distance of ~100 km from the waste origin. For the sake of normalising the models, the energy mix considered is that of the average UK energy mix in 2023.

The overall goal of this case study was to identify the life cycle environmental impacts associated with the treatment of spent ion exchange resins and contaminated PPE through initial thermal treatment methods via the IRIS process and size reduction/encapsulation to provide insights relevant to the strategic research agenda of waste management organisations in Europe.

The functional unit is the processing of 1kg of A_{avg} = 1.5 GBq/kg b/g spent ion exchange resin, and the system boundary is from the receipt of the unprocessed waste to the handoff of a conditioned waste package to the operator of a geological disposal facility.

Full life cycle inventory data is provided in milestone MS16 and will be included in forthcoming publications by the authors.

5.1 Results

The results for the LCA conducted are outlined in Figure 10 with climate change potential indicating that there is a significant change in environmental impact (kg CO2eq.) when comparing novel waste treatment technologies against the baseline of cementation of cementation of RSOW. Cementation of 1kg of RSOW has a climate change potential of 6.39 kg CO2 eq.

An increase in climate change potential has been identified by using novel waste treatment methods combined with the IRIS process. The hot isostatic pressing of IRIS ashes has a climate change potential of 39.8 kg CO2 eq., compared to encapsulation of IRIS ashes in volcanic tuff based geopolymers with 14.15 kg CO2 eq., and pelletization of IRIS ashes through direct compaction with 14.28 kg CO2 eq. However, it should be noted that these versions of the models do not include emissions savings achieved via the avoided GDF space arising from volume reduction: this is the focus of forthcoming work and will affect the overall comparison of options markedly.

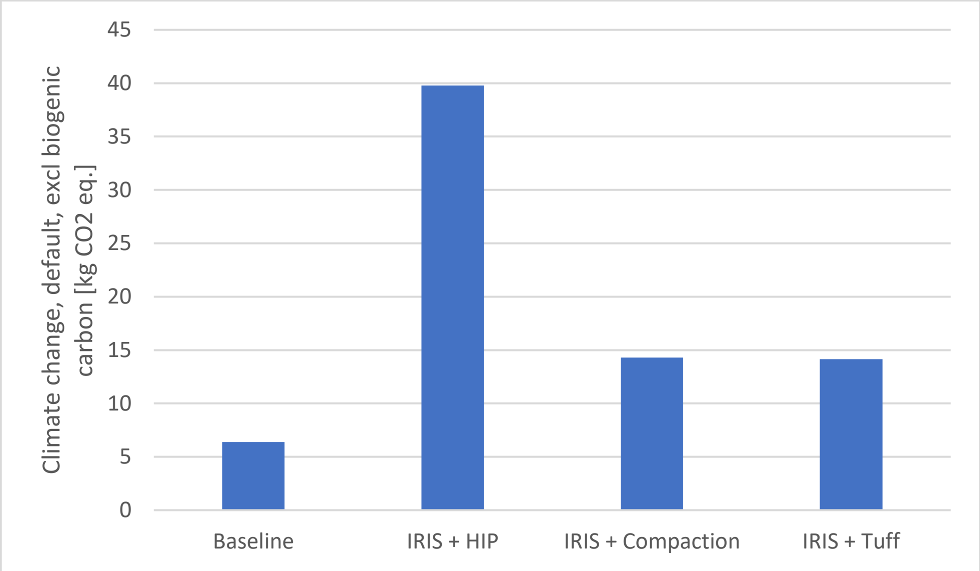

Figure 10: Comparative climate change potential of different RSOW treatment methods.

The majority share of the climate change potential for the above scenarios comes from the IRIS process itself with a contribution of 14.01 kg CO2 eq. to each scenario. As shown in Figure 11, key hot spots within the IRIS process have been identified as the energy requirement for the operation of the rotary kiln and calciner making up ~90% of the total impacts in the climate change potential category and >70% of all other categories except metal depletion, human toxicity (cancer) and freshwater eutrophication.

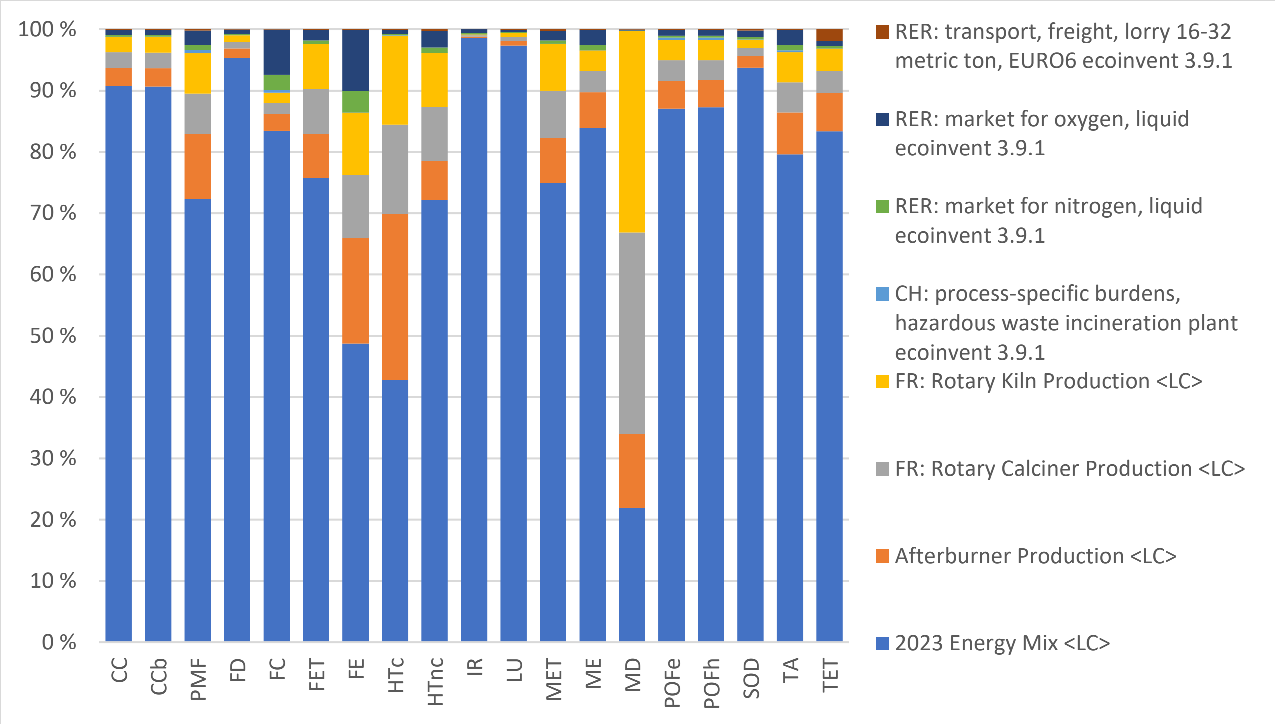

Figure 11: A chart showcasing the life cycle environmental impacts for the IRIS process.

5.2 Conclusions

Firstly, due to the nature of the IRIS process being energy intensive because of the rotary kiln and calciner steps of operation, there is a high degree of environmental impact across multiple impact categories. The purpose of the IRIS process it to firstly reduce the volume of waste which is to go on to further treatment. Ideally, the combined total for the size reduction and encapsulation activities should be less than the baseline but this is not the case. It can be recommended that, from this LCA, steps should be investigated to reduce the energy requirement of the IRIS process to reduce environmental impacts.

Further, comparing the novel treatment technologies against each other even when excluding the IRIS process from the scenarios, there is a significant increase in impact associated with hot isostatic pressing across several impact categories. This is once again due to the energy intense nature of the process as well as the volume of argon required to perform HIP operations. Comparatively, the compaction of ashes using a pelletizer and the encapsulation in volcanic tuff based geopolymers boast promising reductions in overall climate change even if scaled to alone match the baseline. Therefore, it can be extrapolated that when combined with a less environmentally impactful volume reduction activity, these treatment methods could be environmentally beneficial by comparison to the baseline.

Conclusively, there are several research areas that should be the primary focus of research and development of these novel waste treatment methods as regards their sustainability, the most significant of which being the energy consumption of process activities, reductions of which will likely increase the viability of waste treatment methods.

Finally, it should be noted that downstream impacts associated with storage and disposal facilities are not included in the above models, but savings in disposal facility space (and therefore construction requirements) may outweigh the comparative impacts outlined above. This is a focal point of forthcoming work.

6 Work package 7 – Cemented waste and storage

Work package 7 'Innovations in cemented waste handling and pre-disposal storage' focuses on cemented waste handling and pre-disposal storage developing, a specific area of research that is of interest for this case study is the optimising, and implementing monitoring technologies to assist with future store automation and for understanding the "evolution of waste packages during the extended interim storage periods" [18].

Two technologies were identified with their developers as options for life cycle assessment based on their technical maturity and therefore data availability:

- SiLiF neutron and SciFi gamma ray counters
- LoRa radiation monitoring platform

Both technologies detect neutron and gamma ray flux which may indicate changes to the waste within the drum and are suitable to assist with future automation of interim stores. In this study an assumption that both technologies are mounted on the same steel support structure around the drum has been made, however, although not explored in this study the SiLiF and SciFi counters are able to be attached via both a hooking system and also directly on to drum stillages.

6.1 SiLiF & SciFi Counters

SiLiF neutron counters and SciFi gamma ray counters [20, 21] are being optimised in WP7 of PREDIS by INFN for monitoring of LLW and ILW radioactive waste drums. Both the SiLiF and SciFi counters have been developed as simple and compact flux detection devices which can be installed externally around a drum. The SiLiF neutron counter contains a semiconductor detector in the form of a silicon diode with a neutron converter layer of ^{6}LiF on each side. The SciFi gamma ray counter contains a scintillating fibre with a silicon photomultiplier at each end, all contained within an aluminium tube. Currently 3-4 detectors are attached to each drum.

6.2 LoRa Monitoring Platform

The LoRa node monitoring platform [22] is being developed in WP7 by UniPi. It consists of LoRa nodes attached to 2 gamma and neutron detectors. These nodes can then transmit the data from the detectors to a web router meaning the information can be retrieved without needing access to the drum. The use of LoRa provides a benefit of long-range transmission of data with a low power consumption. The lora node is ultra-low power owing to the ability to utilise a power down state and only power on during data transmission, this leads to the benefit of being able to power the nodes using only AA batteries. The node and detectors are housed in individual aluminium cases connected with cables.

6.3 Baseline

The baseline for this study is a standard interim store with no monitoring technology in place and standard storage capacity. The interim store is modelled on a Swiss design with data from ecoinvent and has capacity for 10000m^3 of waste and an operational lifetime of 100 years. The monitoring technologies have been developed using 200L drums during experimentation, therefore these were used to assume that 10000m^3 of waste would equate to a store with capacity for 50000 drums. As the monitors are battery powered in this study, it has been assumed that the batteries would need to be replaced every 10 years for a total of 10 times until the store closes. No replacement of individual components has been modelled.

The goal of this study is to estimate the environmental impacts of producing and implementing monitoring technologies allowing for a higher storage capacity in an example interim store. Transport of monitors is not currently included in the impacts of the technologies due to limited data availability.

The functional unit of this study is per monitored drum in an interim store. The system boundaries start at the production of each component and end with the monitoring technology ready to be recycled/disposed of once the interim store has ceased functioning.

Full life cycle inventory data is provided in milestone MS16 and will be included in forthcoming publications by the authors.

6.4 Results

The baseline impacts for the production of an interim store for low and intermediate level waste suitable for 10,000m3 of waste is 4570.6t CO2 eq. The impacts of producing and applying SiLiF & SciFi monitors to 5% of the waste drums for the entire operational lifetime of the store is 151.6t CO2 eq. and applying the LoRa monitoring platform to 5% of the waste is 160.87t CO2 eq. this is an increase from the baseline of 3.31% and 3.52% respectively to implement the technology. The climate change impacts can also be considered per drum stored and are visible in Figure 12.

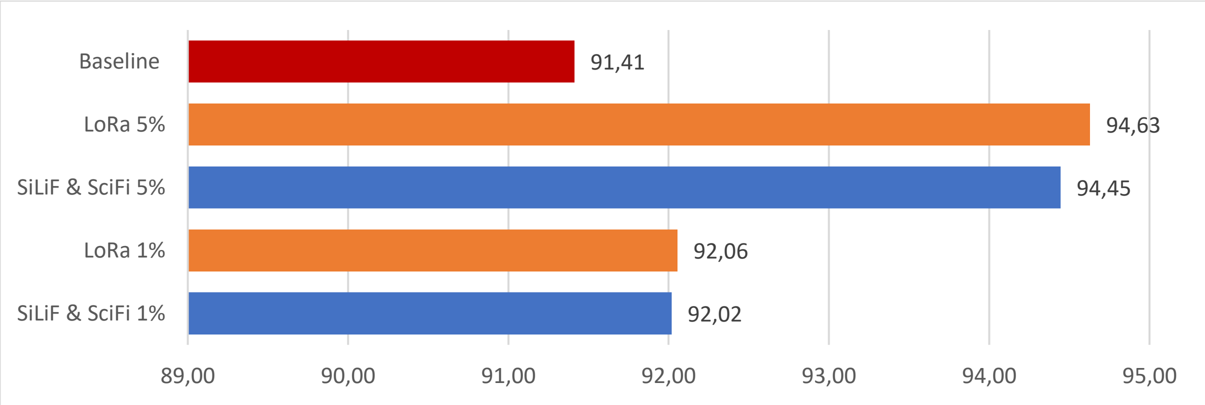

Figure 12: Climate change potential of varying technology and drum % monitored [per monitored drum]

The baseline impact for storing a drum is 91.41kg CO2 eq. this takes the impact of building the store and divides is equally between each drum considering a full store containing 50000 drums. Applying LoRa monitoring to 5% of the drums stored increases the impacts to 94.63kg CO2 eq. or 92.06kg CO2 eq. if only 1% of drums are monitored. Similarly applying SiLiF and SciFi to 5% of the inventory increases the impact per drum to 94.45kg CO2 eq. or 92.02kg CO2 eq. for 1%.

The climate change potential of producing and operating a SiLiF & SciFi monitoring setup made up of 4 SiLiF and 4 SciFi detectors is 42.84kg CO2 eq. The production and operation of each SiLiF neutron counter produces 7.1kg CO2 eq. and the SciFi gamma ray counter produces 3.6 kg CO2 eq. Overall, the hotspot for impacts across all the monitoring technologies is the production of the printed circuit boards (PCBs) and associated integrated circuits (ICs) required. This is due to the intensive process of board fabrication and copper etching during PCB production and the complex manufacturing process of ICs.

Producing a SiLiF counter produces 5.13kg CO2 eq., and if the sensor is battery powered then the impacts increase by 0.2kg CO2 eq for every 10 years in use, therefore for the entire 100 year operational life of the store the entire impacts for the production and operation of the SiLiF sensor is

7.1kg CO_2 eq. Along with the PCB, the polyethylene moderator is also a hotspot of emissions for the SiLiF counter as it makes up 82% of the overall mass. Similarly, the aluminium housing for the counter is notable across multiple categories, especially human toxicity cancer to which it contributes roughly 35% of the impacts.

The impacts of producing a SciFi counter were dominated by the detector PCB and cables (including SMA connectors), though overall the climate change potential of producing the entire sensor is only 1.62kg CO_2 eq. which is lower than the SiLiF neutron detector. If the sensor was battery powered, the impacts are increased by 0.2kg CO_2 eq. for every 10 years in use increasing the impacts of the SciFi sensor production and operation to 3.6kg CO_2 eq. for a 100 year timespan.

The LoRa monitoring platform consisting of 1 node, 2 gamma detectors and 2 neutron detectors produces 46.53kg CO_2 eq. to manufacture and power with the LoRa node contributing 17.62kg CO_2 eq. (37.87%), each gamma detector 4.9kg CO_2 eq. (10.53%), each neutron detector 9.14kg CO_2 eq. (19.64%), and the peripherals (co-axial cables and antenna) contributing the remaining 0.84kg CO_2 eq. (1.8%). When broken down the most impactful component in each piece of equipment is the PCB and ICs as with the SiLiF and SciFi counters. Across all impact categories, the PCB and ICs contribute to 45.6% of the LoRa node impacts, 84.6% of the gamma detector impacts and 91% of the impacts of the neutron detector.

When considering the LoRa monitoring platform as a whole, across all categories the production of both neutron detectors dominates apart from human toxicity (cancer) and terrestrial ecotoxicity whose main contributors are the LoRa node and coaxial cables respectively.

6.5 Conclusions

Currently the impacts of producing all monitors considered in this study are dominated by the production of PCBs and associated ICs used within each. Impacts would be dramatically reduced by minimising the PCBs required, but it is understood that this is practically difficult. Another area of hotspot is the steel support structure required for the LoRa monitoring platform also utilised in this study by the SciFi and SiLiF counters. A reduction in the number and/or size of support structures required, or the use of a less intensive material to produce than steel would be beneficial from an environmental perspective.

The main goal of both technologies is to aid in the automated monitoring of waste in storage, but there is a secondary benefit of potentially increasing the capacity of a store as drums would not necessarily need to be visible to workers for inspection. An increase in capacity of the store would also provide environmental benefits as it would reduce the impact per drum but as it was not possible to ascertain the extent of capacity increase, this has not been further assessed. For consideration however, for every 5% increase in capacity, the impact per drum would reduce by around 4.8% if both technologies were applied.

These monitoring technologies are in development which means approaches and components used evolve and change, future comparisons once the results of the demonstration in an active store have been considered, and potential modification to how monitors are attached to the target drums have been made would be beneficial to realise the positive impact of implementing LCA at an early stage.

7 PREDIS Strategic Research Agenda

The implementation of life cycle tools within the PREDIS project has proved beneficial, aiding the development of environmentally sustainable processes and allowing economic viability to be rigorously and consistently considered during the RD&D phase of technology development. Similarly, the open dissemination of the PREDIS case studies, webinars and training activities have increased awareness across the sector.

It is therefore recommended that these life cycle tools are adopted as part of future nuclear. As such and in line with stakeholder feedback, LCA approaches have been included within the PREDIS Strategic Research Agenda [23].

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