



A review of radioactive waste processing and disposal from a life cycle environmental perspective

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Abstract

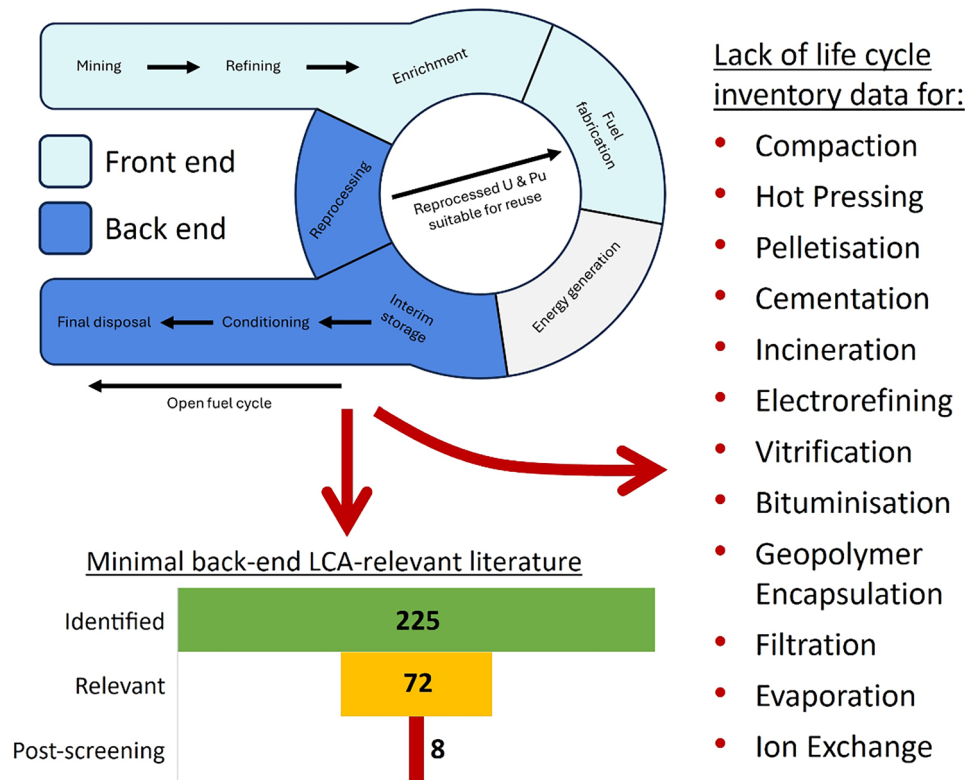
The role of nuclear power in a more sustainable, ‘net zero’ energy sector is an important focal point of research. Given the large volume of existing legacy wastes and the future waste arisings that nuclear expansion would entail, attention is needed in the ‘back-end’ of the nuclear fuel cycle: processing (including treatment and conditioning) and disposal of radioactive waste. The range of waste processing techniques already in operation is broad and complex, and many novel technologies are under development. However, whilst prior work only focused on technology development and direct emissions, particularly in post-processing and disposal, a life cycle perspective is underutilised. This review analyses the landscape of life cycle assessment (LCA) within the nuclear sector, focusing on radioactive waste management, decommissioning and disposal. A literature search yielded 225 journal articles plus additional grey literature, yet only eight relevant LCAs were identified. Most studies identified adopted power generation as a functional unit and focused on nuclear power plants currently in operation. The major research gap identified in this review is the lack of holistic life cycle thinking surrounding radioactive waste management caused by poor granularity of published data related to waste treatment, conditioning and disposal, making strategic analysis challenging from the perspective of sustainability. Future LCA work should focus on technologies and processes in the back-end nuclear fuel cycle with considerable granularity to allow system ‘hotspots’ to be identified and strategic research and policy decisions to be taken. Efforts should also be made to incorporate recent developments in radiological impact assessment methodologies such as UCrad.

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Graphical abstract



Relevant life cycle assessment literature for the back end of the nuclear fuel cycle and the lack of data on wasteprocessing technologies

Keywords Nuclear energy · Nuclear power · Back-end · Decommissioning · LCA · Sustainable engineering

Abbreviations

CGM	Critical group methodology
FU	Functional unit
GDF	Geological disposal facility
GEN IV	4Th generation nuclear power plant
GHG	Greenhouse gas
HHD	Human health damage
HLW	High-level waste
IAEA	International atomic energy agency
ILW	Intermediate-level waste
LCA	Life cycle assessment
LCC	Life cycle costing
LCIA	Life cycle impact assessment
LLW	Low-level waste
LLWR	Low-level waste repository
NPP	Nuclear power plant
RAW	Radioactive waste
SF	Spent fuel
SMR	Small modular reactor
VLLW	Very low-level waste

Introduction

Decommissioning involves the dismantling and demolition of nuclear facilities and removal and/or reduction of radioactive hazards from a nuclear site. A huge range of radioactive materials may be present once a facility has ceased operation, most of which can be categorised as high-, intermediate-, low- and very low-level waste: HLW, ILW, LLW and VLLW, respectively. At the high activity end of the spectrum, HLW incurs significant temperature rises due to its radioactivity, which must be factored into the design of storage and disposal facilities (NDA 2024). This may include spent nuclear fuel (SF), depending on national policy. At the other end of the spectrum, for example, LLW has radioactive content not exceeding 4 Giga-becquerels per tonne of alpha activity or 12 Giga-becquerels per tonne of beta/gamma activity. (NDA 2017) including materials like topsoil from the site. The VLLW category includes any waste of low enough activity that it is suitable for disposal through municipal routes. In most countries, the owner or operator of the nuclear facility is responsible for the safe decommissioning of a plant once it ceases to operate, with most operators

having to prove before the plant is commissioned that there is a financial plan in place to cover the cost of decommissioning (World Nuclear Association 2021).

Once the active/contaminated material is removed from an NPP it usually needs to be processed to immobilise any radionuclides that could migrate during long-term storage and to reduce the volume of material where possible before its final disposal. Many countries generating radioactive waste agree that final disposal should either take the form of a deep geological disposal facility (GDF), ranging from hundreds to thousands of metres below ground level, or a near-surface disposal facility, only tens of metres below ground level. Of the countries planning a GDF, Finland is at the most advanced stage: An operator for its spent nuclear fuel repository at Onkalo has recently applied for an operating license (Posiva 2021), and the Finnish government have published a national programme on the management of spent nuclear fuel and radioactive waste (Ministry of Economic Affairs and Employment 2022a). In the USA, there have been ongoing talks about the Yucca Mountain geological disposal facility in Nevada being open for used fuel but with public objection being so high, this is likely not to come to fruition (US EPA 2022). However, it is important to note that a GDF is essential for the safe storage of heat-generating HLW regardless of whether or not reprocessing is conducted.

Different countries' historical strategies have influenced their preparedness for final disposal, with Finland having not reprocessed spent fuel meaning their waste forms are fewer and the processing options well known (Ministry of Economic Affairs and Employment 2022b). In contrast, countries that have reprocessed used fuel, particularly those with multiple generations of nuclear power plants, have reduced the direct fuel disposal burden but are left with more varied radioactive waste forms and larger volumes of ILW/LLW, with differing processing requirements before final disposal. There are proven benefits to both a closed and open fuel cycle from an energy generation standpoint—where, in a closed fuel cycle, there is scope for the recovery of spent fuel for further enrichment or conversion into mixed oxide (MOX) fuel. All waste processing and disposal decisions have potentially significant environmental and economic impacts and so must be considered carefully.

In addition to existing waste, new waste production rates might increase over the coming decades as decarbonisation policies lead to growth in nuclear power deployment. For instance, the IEA's Net Zero Scenario suggests a tripling of nuclear power capacity by 2030 followed by further increases to 2040 (IEA 2022). Although there is much activity within the nuclear sector towards this target, at current pace, it is unlikely that such a capacity increase will be achievable due to the long construction timeframe for NPPs. Nevertheless, whilst waste produced per unit of electricity

generated is expected to decrease as older reactor designs are replaced, the overall increase in installed capacity will inevitably lead to new waste production in the coming decades as well as the continual generation of waste during the operational phase of existing reactors. Resultantly, an upsurge in reactor decommissioning is inevitable as new reactor designs such as GEN IV and SMRs replace the current active fleets. With these decommissioning activities come an enormous amount of waste which must be processed and disposed of using processes that are potentially material- and energy-intensive. In this context, and with a growing global emphasis on environmental stewardship and sustainability (OECD 2022), it is imperative that the impacts of nuclear decommissioning on the environment are at the forefront of discussions, including when looking to develop and adopt new techniques, all of which will come with varying degrees of environmental and social impact.

In line with the increasing emphasis on environmental sustainability, there is increasing interest in following the waste hierarchy and its associated circular economy principles. This encourages reuse and recycling of waste materials as opposed to disposal and is highly applicable to the nuclear industry (for instance in the decontamination and use/recycling of surface-contaminated metals). Such approaches are in need of examination throughout the back-end of the fuel cycle and may themselves incur sustainability impacts from additional processing steps which will necessitate impact minimisation and the balancing of benefits against detriment in a holistic manner.

Therefore, it is important that relevant studies such as life cycle assessment (LCA) are undertaken to aid decision-making and technology development based on holistic, cradle-to-grave information. This paper will analyse the current landscape of nuclear waste processing technologies and the existing LCA focusing on back-end nuclear processes.

European nuclear waste inventory

As shown in Table 1, the volume of radioactive waste in storage across the EU as of 2016 is 983,000 m³ (this volume includes the UK inventory). The volume of radioactive waste disposed of in 3 years from 2013 to 2016 was 167,000 m³, and this is expected to increase through to 2030 as more reactors come offline, as shown in Table 2. It is important to note that these forecasts end in 2030, but further wastes will arise for decades, leading to much higher volumes than those shown in the tables: for instance, future arisings of VLLW—a sub-category of LLW comprised of waste that can be safely disposed of with municipal, commercial, or industrial waste, or can be disposed of in specified landfill—in the UK alone are estimated at 2,750,000 m³ (Nuclear Decommissioning Authority 2023). The majority of this waste, especially LLW, ILW and HLW, will need to

Table 1 EU radioactive waste inventory (European Commission 2019)

Waste Category	EU RAW amounts (m ³ , rounded to thousands)					
	Stored		Disposed		Total	
Year	2013	2016	2013	2016	2013	2016
VLLW	237,000	234,000	279,000	369,000	516,000	603,000
LLW	428,000	417,000	2,025,000	2,102,000	2,453,000	2,519,000
ILW	326,000	326,000	12,000	12,000	338,000	338,000
HLW	6000	6000	0	0	6000	6000
Total (m3)	997,000	983,000	2,316,000	2,483,000	3,313,000	3,466,000

Table 2 Future arisings of EU radioactive waste (European Commission 2019)

	Future RAW and SF amount estimates (m ³)				
	VLLW	LLW	ILW	HLW	SF
2016	603,000	2,519,000	338,000	6000	58,000
2030	1,360,000	3,322,000	455,000	9000	76,000

be treated before final disposal to produce a more stable waste form. These large waste volumes across Europe necessitate a focus on the back-end nuclear fuel cycle from an environmental sustainability perspective.

Nuclear fuel cycle back-end

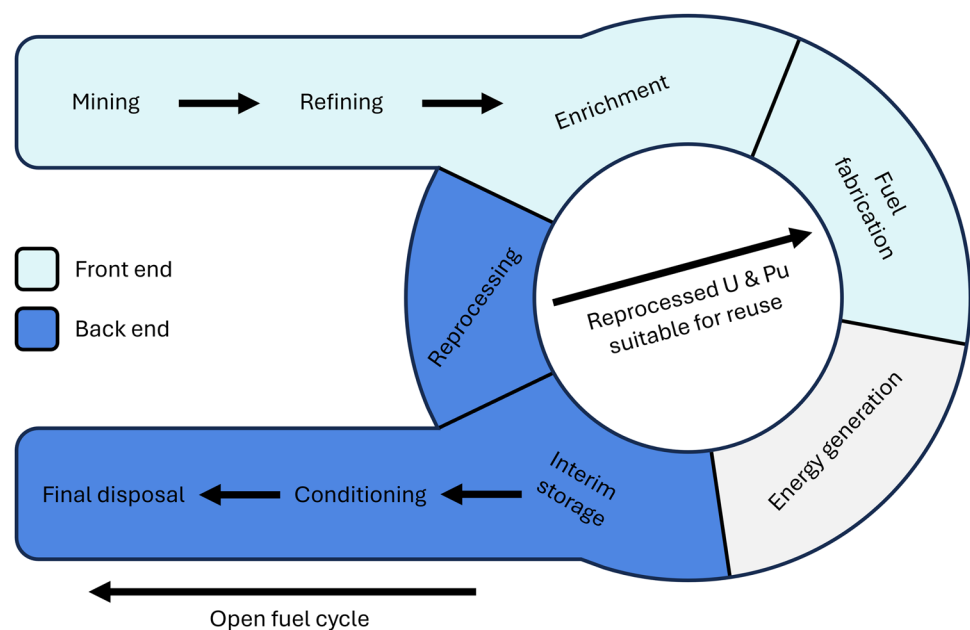
As shown in Fig. 1, the nuclear fuel cycle can be split into two sections, the front-end and back-end, with the power generation acting as a ‘dividing line’ between the two (Choppin et al., 2013). Front-end operations generally include mining, refining, enrichment, fuel fabrication and

any other activities leading up to fuel irradiation within the power plant. Back-end processes are considered as any activities that occur post fuel irradiation which include interim storage, reprocessing (when concerning a closed fuel cycle), waste processing, storage and final disposal.

Initially, radioactive waste is stored in an interim storage facility either to decay in radioactivity or until a final disposal route is available. Some wastes are stored until they naturally decay to limits low enough for disposal via lower activity waste routes.

Waste processing covers all activities undertaken to make waste suitable for disposal. This contains waste treatment steps such as compaction, incineration and other state transformative activities. It also includes conditioning—the consolidation of the treated waste into a solid form ready for disposal, i.e. through encapsulation in cement or via vitrification. Once conditioned, the waste is then further stored awaiting final disposal.

In the case of a closed nuclear cycle, the SF is not processed for disposal; it is reprocessed. After re-enriching or conversion to MOX fuel, it can be reintroduced into Gen III/

Fig. 1 The nuclear fuel cycle (adapted from (IAEA 2011))

III + reactors where 25–30% more energy can be released from the original radioactive material (IAEA, 2020). In the case of fast reactors, this increase in energy yield is much higher. If the used fuel is not to be reprocessed or can no longer be reprocessed, it will then be immobilised for disposal.

The waste processing techniques throughout the above stages vary greatly based on wasteform, radioactivity and location. Various techniques are currently in use or under development, as outlined by the examples in Table 3.

Most countries with radioactive waste are considering deep geological and/or near-surface disposal facilities for the final disposal of waste with different levels of maturity of implementation. Repositories already exist in many countries at ground level such as the low-level waste repository (LLWR) in the UK and below ground level at facilities such as the SFR final repository in Sweden for short-lived radioactive waste (SKB 2021). Deep geological disposal is the official policy for the disposal of ILW and HLW in multiple countries (but note that SF is not considered a waste in all countries). The design of each repository is dependent on the geology of the surrounding area, and Finland's Onkalo repository is the most advanced design, set to be operational in the mid-2020s. Onkalo will be the first repository licensed for the disposal of SF (Vira 2017) (Fig. 2).

LCA

Life cycle assessment (LCA) is 'an environmental management tool that helps to translate life cycle thinking into a quantitative measure of environmental sustainability of products, processes or activities on a life cycle basis' (Azapagic et al. 2011). LCA is useful for finding the overall environmental impact of a product/process and can identify emission 'hotspots' so targeted emission reduction strategies can be implemented. LCA can also be used to compare products/process in advance of their application driving reduction in both emission and overall cost. According to the international organisation for standardisation (ISO) standard 14,040/14044, life cycle assessment should follow four steps:

Goal and scope analysis

In this step, it is decided how much of the product/process life cycle will be assessed and what the goal of the study will be, whether that be discovery of overall environmental impact, or investigation of emission 'hotspots' (process areas of significant environmental impact). The system boundaries are defined, such as cradle-to-grave, encompassing the whole life cycle or a smaller boundary such as cradle-to-gate, gate-to-grave, etc. If this is more suitable for the process being studied. Functional units (FU) are defined as the

unit of assessment, and the limitations and assumptions are described.

Inventory analysis

Inventory analysis describes the material and energy flows within the system, where environmental burdens of the activity under study are identified and quantified. This includes procuring data from reliable sources so that the outputs of the LCA study can be trusted.

Impact assessment (LCIA)

In this stage, the environmental burdens are converted into environmental impacts, classified into themes such as climate change, loss of biodiversity, human toxicity, etc., depending on the goal of the study. Commonly used LCIA methodologies include CML (Guinée and Lindeijer 2002), ReCiPe (Goedkoop et al. 2009), Eco-indicator 99 (Goedkoop and Spriensma 2001) and Impact 2002+ (Jolliet et al. 2003). According to a survey (iPoint 2018), the majority of practitioners use the ReCiPe methodology. Some nuclear LCA studies have also included radiological impact assessments of nuclear energy generation, though no standardised methodology currently exists.

Interpretation

The final stage involves analysis of the resulting impact categories, including identification of hotspots, sensitivity analysis and selection of the best scenarios/alternatives.

Methods

The sources selected were Scopus, Google Scholar and The University of Manchester (UoM) library. Scopus was selected as an internationally-acclaimed source of peer-reviewed publications with an independent Content Selection & Advisory Board comprised of leaders in their respective fields. Google Scholar was selected as a broader search engine to gather more niche literature sources including those not published in scientific journals (grey literature). The University of Manchester library was selected as a supplement to gather local research including reports and PhD theses. A specific date field of 2010–2022 was applied on the Google Scholar and Scopus searches (unavailable with UoM) to encompass the decade prior to the commencement of the EU PREDIS project. Due to the very limited number of relevant articles despite the increased application of LCA in recent years, the authors deemed it extremely unlikely that relevant articles would be found prior to 2010.

Table 3 Description of radioactive waste processing techniques

Waste processing stage	Waste processing method	Description	Types of waste treatable	References
Treatment	Compaction	Reduction of overall volume of waste by compaction. May include pre-treatment such as shredding to increase volume reduction factor	Fuel assemblies, filter cartridge inserts, non-combustible solid waste	(Garamszeghy 2011) (IAEA 2021) (VGB PowerTech 2012)
	Hot pressing	Similar to compaction but applying isostatic pressure at high temperature in a vessel. It can be applied to wet wastes with a potential volume reduction factor of 90%	Radioactive ash waste	(Garamszeghy 2011) (Heath 2017)
	Pelletisation	Radioactive waste is formed into pellets and then grouted into a drum	Most solid wastes	(Garamszeghy 2011) (Matsuda et al. 1994)
	Incineration	Combustion of flammable wastes with the goal of volume reduction and removal of organics and liquids to meet waste acceptance criteria	Solid and liquid radioactive waste	(Deckers 2011; IAEA 1992)
	Electrorefining	Separation of specific nuclear species from metallic waste via electrolysis-based refining	Metallic radioactive waste	(Lewin and Harrison 2015) (Allensworth et al. 2013) (Benedict et al. 2007) (Bourg et al. 2012)
	Filtration	A commonly used method for separation and purification of liquid waste streams, also used to separate radioactive particles from contaminated surfaces and soils	Liquid/aqueous radioactive waste	(Abdel Rahman et al. 2011; IAEA 2004)
	Evaporation	Reducing the volume of liquid radioactive waste by heating the liquid waste to its boiling point	Liquid/aqueous radioactive waste	(Calloway et al. 2003; Godbee 1973)
	Ion exchange	Passing the waste through a column filled with a solid ion exchange material, such as a resin or a zeolite, which has a specific affinity for the ions to be removed	Liquid/gaseous radioactive waste	(Kim et al. 2012; IAEA 2002)
	Decontamination	Removal of surface contaminants within nuclear facilities, such as piping systems, internal surfaces of hot cells, tanks, etc. Decontamination is generally achieved through chemical and mechanical means though various other methods exist, e.g. laser-induced chemical reactions. The removal of contamination produces smaller waste forms and liberates the remaining material to lower waste categorisations	Solid radioactive waste	(Wille 1987; Yamamoto et al. 2020; Hirabayashi et al. 2000)

Table 3 (continued)

Waste processing stage	Waste processing method	Description	Types of waste treatable	References
Conditioning	Cementation	Waste is encapsulated in cement due to its low permeability once cured meaning limited leaching of radionuclides. Ordinary Portland cement is common though different formulations exist for enhanced immobilisation of specific waste types	Liquid and solid radioactive waste	(Kim et al. 2021) (Bart et al. 2013)
	Vitrification	Converting radioactive waste into a glass-like solid by mixing it with a binder, such as borosilicate glass, and heating it to a high temperature creating a solid, stable and durable form of waste that can be safely stored and transported	Liquid and solid radioactive waste	(Thorpe et al. 2021; Walling et al. 2021)
	Bituminisation	Mixing the waste with bitumen and then solidifying the mixture by heating it to a high temperature. The resulting solid material is highly durable and resistant to water and other environmental factors, which makes it suitable for long-term storage and disposal	Liquid and solid radioactive waste	(Ojovan and Lee 2005; IAEA 1993)
	Geopolymer encapsulation	Mixing the waste with a geopolymer binder, which is made from a mixture of aluminosilicate-based materials and a strong alkaline activator. This creates a solid, stable and durable form of waste that can be safely stored and transported	Liquid and solid radioactive waste	(Kriven 2021; Reeb et al. 2021)

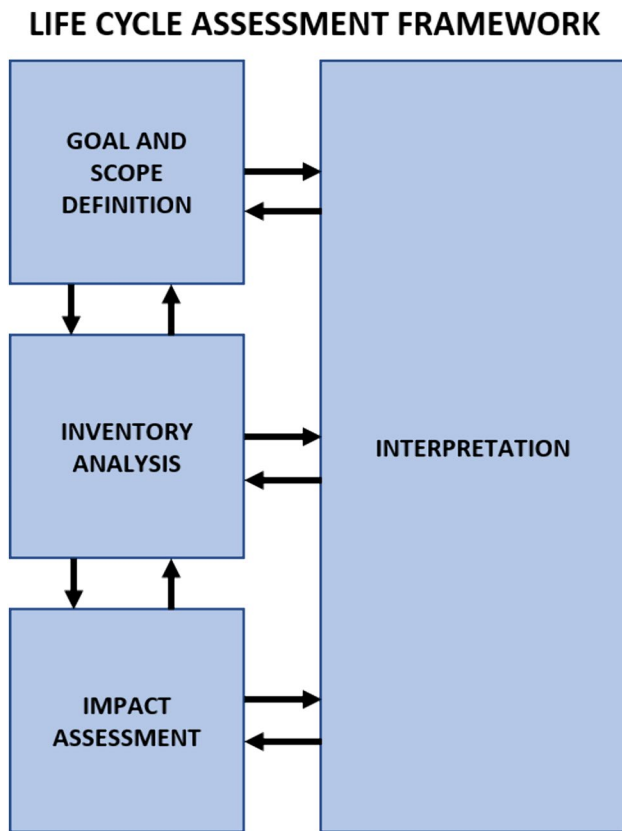


Fig. 2 Life cycle assessment framework according to ISO 14040 (adapted from (ISO 2006a))

The key words selected for each of the source searches included common terms and term groupings such as ‘radioactive waste/nuclear waste’, ‘back-end’, ‘liquid’ and ‘solid’ with optional terms including ‘organic’ also being included. Synonyms which are prevalent within the nuclear industry such as ‘decommissioning’ and ‘end of life’ were also considered. Due to the differing functionality of certain search engines, specific strings of search terms had to be formulated differently in order to yield appropriate results, as indicated in Fig. 3.

The specific search parameters used for this review are shown in Fig. 3, alongside the number of results yielded. Searches were conducted in February and September 2022.

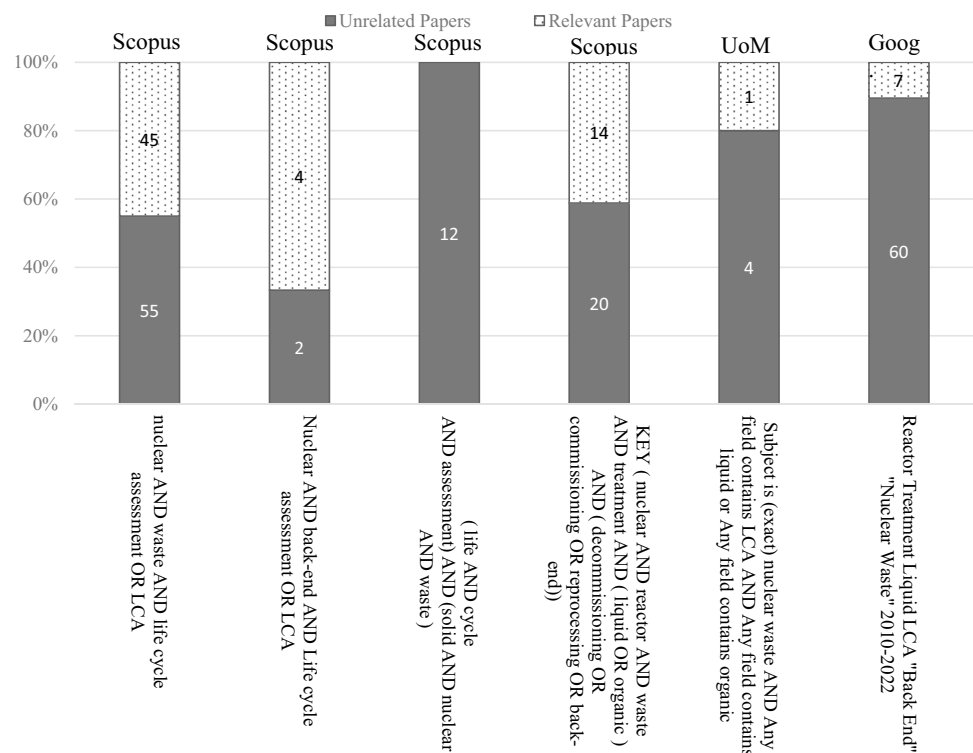
Following the initial search (see Fig. 3), the results were screened for relevance using the following main criteria:

- Specific mention of radioactive/nuclear waste processing technologies
- Specific mention of liquid and/or solid radioactive/nuclear waste
- Any mention of life cycle assessment or life cycle costing

A specific criterion was made for papers of partial relevance which provided useful insight into the fundamental understanding of the review topic or mentioned technology which has not yet been implemented, e.g. those for use on GEN IV reactors (Koltun et al. 2018).

The literature which was of no relevance was simply rejected from the review if none of the criteria above

Fig. 3 Results from the literature review



were satisfied. This is notable in the search results shown in Fig. 3, '(life AND cycle AND assessment) AND (solid AND radioactive AND waste)', where 12 search results were produced but none were of relevance to the literature review as they focused on non-nuclear technologies.

Many extensive life cycle assessments of nuclear power exist but were not explicit about their coverage of waste processing, or used data that lacked an explicit description of the waste processing or disposal route being considered (Warner and Heath 2012; Nian et al. 2014; Lenzen, 2008).

Of the 225 search results screened after identification through Scopus, Google Scholar and UoM library (see Fig. 2), 31.69% were relevant to this study of nuclear LCA. The yield of results was as predicted, with few making it past the screening process due to lack of relevance. The Scopus library of published literature proved to be the most effective and Google Scholar to be the least effective based on the proportion of relevant publications. The University of Manchester digital library yielded only a single relevant paper, which was also found via the other literary sources.

Due to the limited volume of literature available in this field, grey literature was also screened separately. This included reports by the International Atomic Energy Agency (IAEA) and other government agencies which detailed nuclear 'back-end' processes including waste processing and final disposal alongside discussion of guidelines and policy, but due to the lack of inclusion of LCA methodology within these reports, they did not meet the established criteria and, therefore, did not pass the screening process.

For the relevant literature, the process of 'snowballing' was also applied by reviewing the literature cited by each study to identify any remaining items of relevance.

Results and discussion

The purpose of this section is to analyse the existing literature regarding both liquid and solid nuclear waste within the scope of LCA. The discussion below is structured to address the key elements of LCA as defined in the ISO 14040–44 standards (ISO 2006a), namely the overall goal and scope, the system boundaries, functional unit, inventory data sources, impact assessment methods and results.

Overall, it is clear from the literature search process that the majority of nuclear-related LCA studies have used the entire fuel cycle as their system boundary, in which the granularity of back-end processes is minimal; often the entire back-end is represented as simply decommissioning followed by disposal, with little commentary or detail provided within these steps.

Consequently, LCA data related specifically to the back-end of the fuel cycle is limited. This section will review

the information available to conduct a gap analysis and ultimately inform the direction of future data gathering.

Table 4 shows the final selection of screened studies applying LCA principles to the nuclear back-end, demonstrating the limited number of studies in the literature.

Alongside this lack of data, some may become outdated as policy changes are made. For example, an in-depth LCA study of the effects of decommissioning the Magnox reactor fleet across the UK (Wallbridge et al. 2013) is already out of date due to strategy changes affecting the decommissioning timeline: Though the new strategy appreciates the benefits of deferred decommissioning, 'it is not appropriate as a blanket strategy for all reactors in the Magnox fleet' and 'for some sites this will result in their decommissioning being brought forward' (Nuclear Decommissioning Authority 2021). Such changes to decommissioning timelines have consequences on material usage, background energy mix and disposal route options applied to the processes undertaken, and therefore on the overall environmental impact.

The scarcity of back-end fuel cycle LCA information appears to be caused by two predominant drivers: firstly, much prior LCA work in the energy sector has focused on comparison to other energy generation techniques, leading to a focus on the generation process and oversimplification of the disposal process where waste processing is missed, e.g. (Gagnon et al. 2002; Santoyo-Castelazo et al. 2011; Siddiqui and Dincer 2017), particularly affecting nuclear power due to the complexity and variety of its waste processing requirements. Secondly, there is often a lack of clarity over the exact processes associated with power plant end-of-life and used fuel processing, in some cases accentuated by a lack of back-end fuel cycle policies in the country under assessment (Lee et al. 2000; Turconi et al. 2013).

Another possible reason for the lack of attention paid to the back-end is the apparent dominance of front-end activities in environmental impacts: When the entire nuclear life cycle is considered, existing studies suggest that the front-end processes (mining, separating and purifying) account for > 70% of the overall environmental footprint, in part because most of those processes have remained similar since their development in the 1950s–1960s (Poinssot et al. 2016). Similar conclusions, i.e. that the front-end is the major contributor to the emissions associated with nuclear power generation, have been reached by other LCAs (Lenzen 2008; Warner and Heath 2012) Whilst this front-end dominance may be the case, improved granularity of data on the back-end processes would help to verify this claim and may well offer help to identify opportunities to minimise waste and reduce overall environmental impacts. This uncertainty is further accentuated by the huge variation in GHG emission factors in nuclear LCA studies 'up to one order of magnitude', although this is largely attributable to whether a study included uranium enrichment in the life cycle, and to a lesser

Table 4 Existing nuclear LCA studies reviewed

Paper	Functional unit	System boundaries	Life cycle inventory data source	Radiological impacts reported?	LCIA methodology	Life cycle stage considered in study					Final disposal
						Front-end	Operational lifetime	Waste processing	Reprocessing	Decommissioning	
(Wallbridge et al. 2013)	Decommissioning of one UK Magnox reactor	All stages of decommissioning (except HLW)	Primary—Trawsfynydd NPP Background—Ecoinvent	No	CML 2001			X		X	X
(Pomponi and Hart 2021)	Life cycle of a European Reactor	Full life cycle of an NPP	Primary data from an EDF Energy report (EDF 2016) Background—Eora database (KGM 2024, Ltd., 2024)	No	IPCC GWP100	X	X			X	
(Fthenakis and Kim 2007)	Whole nuclear life cycle	US nuclear fuel cycle	Other pre-existing LCA studies Background—Ecoinvent	No	None declared	X	X	X		X	X
(Lee et al., 2000)	Delivery of 1 GWh electricity generated from 11 PWRs to consumers	Mining/milling and normal operation of plant (including the waste processing in case of once-through cycle)	Primary data—report from (Drecier, 1995) Secondary data—Fabrication de Combustibles and BNFL	Yes	None declared	X	X	X			
(Paulillo et al. 2021)	Management of used nuclear fuels from AGR containing 1 t of uranium pre-irradiation	Foreground—historical approach to used nuclear fuels reprocessing Background—all other processes that exchange materials and energy with the foreground	Ecoinvent	Yes	Ucrad			X	X		X
(Koltun et al. 2018)	1 MWe	Full life cycle of an NPP	Background—Simapro database (Simapro 2024)	No	None specified	X	X	X		X	X

Table 4 (continued)

Paper	Functional unit	System boundaries	Life cycle inventory data source	Radiological impacts reported?	LCIA methodology	Life cycle stage considered in study				
						Front-end	Operational lifetime	Waste processing	Reprocessing	Decommissioning
(Godsey, 2019)	3.6×10 ⁸ MWhe by SMR	Full life cycle of an SMR	Based on a theoretical reactor built in Australia, therefore, inventory data are taken from Australian conditions	Yes	ReCiPe 2008	X	X	X		X
(Guidi et al. 2010)	Decontamination of a 1 m ² surface	Production of decontamination coating to storage of waste produced	Ecoinvent The flowchart is modified from (Drecier, 1995) and (Frischknecht et al. 2000)	Yes	Eco-indicator 99			X		

extent the methodology and technological approaches considered (Turconi et al. 2013).

The limited research in this area suggests that solid wastes may be responsible for a greater environmental impact than liquid wastes due to the latter's lesser volumes as can be seen in the results presented by Wallbridge et al. (2013) where liquid wastes (sludges and effluent) produced in the decommissioning of an NPP made up 6 waste packages whereas the solid contaminated waste required > 6970 packages. (In this study, 'packages' were simplified for LLW to 2.2 t steel and a ratio of 2:1 of waste to grout, and for ILW 4.2 t steel and a ratio of 1:1 of waste to grout. These values were averages across multiple waste package types.) The smaller number of packages for liquid waste is due to liquid effluents predominantly being treated, yielding further solid waste, and discharged whilst solids are more likely to be stored during the operational phase. It is typical for solid wastes to be concrete, steel and other contaminated materials from decommissioning activities which are comparatively more massive. However, the greater prevalence of solid waste generation within decommissioning activities means that, over the life of a plant, their production rates vary more than those of liquids, which typically come from analysis and maintenance. These differences should be taken into consideration when considering the granularity of LCA modelling.

Goal definitions

The goals of each LCA study identified in this review (Table 4) were either related to the whole life cycle of NPPs, back-end waste processing technologies or reactor site decommissioning. From all the papers reviewed, most gave a clear goal and scope outline within the first few subsections whilst one did not (Pomponi and Hart 2021) (though it could be ascertained through context) whilst others compared pre-existing LCA studies, and therefore, the goal and scope for each were not described (Fthenakis and Kim 2007). The paper by (Guidi et al. 2010) is the only LCA study whose goal does not consider large-scale NPP processes but instead focuses on a specific waste form's treatment and aims to quantify the impacts of decontaminating a surface using a novel technology in comparison with an existing approach.

System boundaries

System boundaries were well defined in all papers. The study by Wallbridge et al. (2013) offers the most comprehensive look at applicable system boundaries for this review. It encompassed the stages of decommissioning—including the waste arising from decommissioning activities, temporary storage and final disposal of nuclear waste.

Pomponi and Hart (2021) acknowledge the omission of decommissioning activities in existing literature prior to

their assessment of a European PWR, a notable case study being Ding et al. (2017) with the decommissioning phase being absent in their assessment of energy infrastructure in China, but still encompassing back-end processes within the system boundaries.

Fthenakis and Kim (2007) also mentions the 'outdated information' within LCA databases for waste processing activities and decommissioning stages, leading to a lack of any specific analysis within their assessment. Godsey (2019) also references the lack of back-end data available, attempting to draw additional information in their assessment of SMRs in the US nuclear fuel cycle from other sites, specifically the VVER facility in Lubin, Germany, noting the limitations of this comparison. The authors note that, of all papers in this review, only one (Guidi et al. 2010) focused on the environmental impacts of a specific waste treatment method: the treatment of contaminated surfaces through the use of strippable coatings and vacuum technology.

There is an inherent uncertainty in developing accurate models related to decommissioning as a result of the potentially large timescales involved with resultant differing energy mixes and disposal routes, as well as the policy changes that may arise; this is acknowledged by Paulillo et al. (2021) and Koltun et al. (2018) within their assessments. Paulillo et al. do specifically reference the waste generated through reprocessing scenarios (i.e. via THORP), but a granular assessment of waste management and plant decommissioning is outside of its scope. This is also true of Lee et al. (2000) which focus more so on spent nuclear fuel in the case of the Korean once-through cycle.

There is a general focus on the system boundaries being the whole reactor site including during the operational/power generation period without a great deal of consideration for the back-end of the nuclear fuel cycle. However, in recent years, there has been an increase in the consideration of decommissioning projects, i.e. the Magnox fleet in the UK (Wallbridge et al. 2013) which include the disposal of various types of radioactive wastes. With further expansion of the system boundaries to include waste processing and disposal methods, insight could be gained as to the impacts of these processes as waste volumes and therefore processing requirements will increase.

Functional units

A functional unit (FU) is used as a 'quantified description of the function of a product [or system] that serves as the reference basis for all calculations regarding impact assessment' (Arzoumanidis et al. 2020). Of the limited number of LCA studies on nuclear energy generation/decommissioning, the majority use the entire life cycle of a NPP, or a unit of electricity generated within this life cycle. For instance, Koltun et al. (2018) selected 1 MWhe of generation as the

FU when assessing the potential impacts of GEN IV plants, and similarly, (Lee et al. 2000) chose a FU of 1 GWh electricity delivered to consumers. Only one paper considers specifically a waste treatment process (Guidi et al. 2010).

In Wallbridge et al. (2013), the functional unit was the ‘decommissioning of one Magnox power plant’. This is unique among the identified papers and aligns with the fact that this was the only paper focused on the decommissioning of a single NPP. Even in this case, the global warming potential was also expressed per kWh generated in order to contextualise against other studies such as those above.

Life cycle inventory (LCI) data sources

Almost all papers provided detail on their data sources, with data on the foreground system primarily arising directly from power plant operators or from material published by plant operators. Background data were typically sourced from the database Ecoinvent. However, some papers provided less detail, such as Koltun et al. (2018) which only specifies the source of their background data as ‘Australian conditions’.

The Ecoinvent database, upon which these studies rely, has little data directly related to back-end processes and most is Swiss-centric due to the database’s origins in Zurich, Switzerland. For example, the data on the environmental impacts of the construction of a geological disposal facility for nuclear waste are based on a Swiss design; therefore, if it is used in an LCA study, it must be edited to reflect other countries’ GDF designs, as no two are the same due to differences in host rock, depth, engineering approaches, etc. In some cases, as seen in Wallbridge et al. (2013), the disposal facility model is simplified and condensed to contain only its steel and concrete components, reducing the likelihood of error but simultaneously risking an underestimation of the true impacts.

There may also be data specificity and age implications from the use of Ecoinvent by the majority of LCA practitioners. For example, most data for countries other than Switzerland are modified datasets based on original Swiss data as opposed to being built from the ground up. The problem of data being outdated is especially prominent in nuclear processes: for instance, the data on electricity generation from boiling water reactors originate from the period 1990–2015; similarly, the process of constructing a nuclear fuel factory has not been updated since 2000, and the data for the construction of a nuclear waste repository have not been updated since 2002 (Ecoinvent 2023). This does not mean that Ecoinvent should be avoided—on the contrary, it has the most complete datasets available—but it does highlight the lack of alternative nuclear sector datasets for LCA practitioners due to insufficient work in this area. Therefore, these existing datasets must be carefully assessed prior to use to ensure

their validity in a modern model. Ecoinvent is transparent and provides comprehensive documentation on the source of data, and this should be evaluated to ensure that inappropriate data and assumptions are not implicit across multiple LCA models throughout the literature.

Software and impact assessment methodologies

Of the LCA studies reviewed only four discussed their impact assessment methodology: CML2001 (Wallbridge et al. 2013), Eco-indicator 99 (Guidi et al. 2010), ReCiPe (Godsey 2019) and UCrad (Paulillo et al. 2021). Other literature identified by this review, which did not pass the screening process due to a lack of LCA within the nuclear context, also applied the CML (Guinée and Lindeijer 2002) and ReCiPe (Goedkoop et al. 2009) methodologies most frequently. The study conducted by (Godsey 2019) addressing the US nuclear fuel cycle provides significant discussion and justification around their choice to use the older ReCiPe 2008 method as opposed to ReCiPe 2016 due to validity uncertainties in their software.

Whilst ISO 14040 and 14,044 do not require justification of the selection of an impact assessment methodology, they do specify that it should be clearly reported, and that the choice of metrics should align with the goal and scope of the study (ISO 2006a, ISO 2006b). Consequently, of the studies reviewed here, the only ones compliant with the ISO are Wallbridge et al. (2013), Godsey (2019), Guidi et al. (2010) and Paulillo et al. (2020).

So far, radiological impacts have only been considered in nuclear LCA studies to a relatively basic standard due to the simplicity of existing LCA impact assessment models for radiological discharges. Recently, a paper was published by Paulillo et al. (2020) comparing two methodologies for quantifying ionising radiation impacts: UCrad and critical group methodology (CGM). These were compared to a pre-existing approach used in LCIA called Human Health Damage (HHD) (Frischknecht et al. 2000) which has been described as ‘recommended but in need of some improvements’ (Hauschild et al. 2013). Other radiological impact methodologies proposed exclusively for LCA applications have been reviewed but were not considered sufficiently comprehensive (Paulillo et al. 2020). The outcome of the review was that ‘characterisation factors from the CGM methodology are strongly affected by radioactive decay at low half-life and by dilution at large distances. Conversely, UCrad factors are not affected by dilution and are affected less than CGM by radioactive decay’. Therefore, UCrad is more appropriate than CGM for LCA as it is consistent with the general approach used in LCIA. There is a prescribed necessity for the further exploration of radiological assessment methodologies which could be applied to nuclear-related LCA, both back-end and otherwise. For instance,

approaches included in the most common life cycle impact assessment methodologies are based on absorbed dose or exposure relative to reference isotopes such as Co-60 (Huijbregts et al. 2016) and U-235 (European Platform on LCA 2022), whilst non-LCA studies have considered other metrics such as collective dose (person-Sieverts) over a million years and Tier 1 ERICA score (Abrahamsen-Mills et al. 2021).

Although not an LCA study, Poinssot et al. (2016) discussed the opportunities available to decrease the environmental footprint of nuclear energy generation using similar indicators such as GHG emissions, atmospheric pollution (a quantification of the combined mass of SO_x and NO_x released per GW electrical power), land use, water consumption/withdrawal and the production of technological waste. Similarly, Sheldon et al. (2015) described the impact of the long-term storage of radioactive waste and impact of a catastrophic event which they have defined as the probability of total failure multiplied by the replacement energy costs.

The choice of impact assessment methodology can have a great influence on the reported impacts. As the ISO standard does not provide recommendations on the method which should be used, many organisations and governmental bodies have compared and evaluated different methodologies and provide their own recommendations for the best available approach as outlined by (Rosenbaum et al. 2018). The European Commission recommends the use of ILCD (EC-JRC 2011) and Environmental Footprint (EF) (European Commission 2021), the US Government recommends TRACI, though it has noted in best practice guidance that this LCIA methodology has not been updated since 2021 and, therefore, has ‘recommended to utilize the IPCC AR6 GWP characterization factors for translation of GHG emissions to Global Warming Potential impacts as a replacement for the factors in TRACI’ (U.S. DOE 2022). There does not exist a recommended LCIA methodology within the UK or wider nuclear industry. LCA of nuclear processes might benefit from the adoption of an LCIA methodology to assist in the comparison of results as it would allow assessments from multiple sources to be comparable between each other, aiding in decision-making at both an application level and policy making level.

LCA results

Due to the variety of system boundaries within the LCAs screened, the direct comparison of their results is difficult, although many share similar conclusions.

Firstly, the mining/milling of virgin resources such as uranium from open-pit mines appears to be a prevailing factor in several studies. For instance, when assessing the viability of SMRs, Godsey (2019) found that the LCA had a strong dependence on the boundary conditions applied and

when incorporating the front-end, the mining practices utilised were an area of particular sensitivity, narrowed down to the source of the energy used for these processes. This resulted in recommendations that were also reflected in an LCA conducted by (Lee et al. 2000), who recommend that mining practices should be considered due to their dominant impacts.

Parallel to the above, (Fthenakis and Kim 2007) found that in their LCA based on the nuclear fuel cycle in the USA, front-end practices were also dominant citing the diffusion enrichment of nuclear fuel as the most prominent factor contributing ~ 50% of total GWP in their baseline scenario with limited impacts from sensitivity analysis.

The recycling of spent nuclear fuel to prevent the mining of virgin material was discussed in an LCA by Paulillo et al. (2021) which looked at reprocessing scenarios in the UK and argued that it was essential for policy makers to consider the reimplementation of reprocessing of SF to reduce environmental impacts.

When directly considering the back-end of the nuclear fuel cycle, Wallbridge et al. (2013) highlighted the impacts of the decommissioning of the Trawsfynydd site showcasing the dominance of the deconstruction, disposal and temporary storage—mirrored by Guidi et al. (2010)—which were notable hotspots. The conclusion of the LCA, based on the identification of the model’s sensitivity to energy mix, was to suggest that a period of quiescence could be considered to allow for the national grid to decarbonise. As described in Table 4, all other studies screened also considered varying aspects of the back-end of the nuclear fuel cycle but with limited data resolution, i.e. taking a top level view of back-end processes as opposed to individual waste processing/disposal pathways. For example, within their LCA of the entire SMR life cycle, Godsey (2019) simplified ‘waste management’ to comprise only the steel and cement required for the conditioning of waste rather than individual waste processing pathways for different waste types and their associated energy requirements. This lack of granularity means that accurate assessment of the impacts/comparison between studies of individual back-end processes is not possible.

Waste processing options

As outlined in the methods section, most nuclear-related LCA studies and reviews were not explicit about the waste treatment/conditioning processes considered within their studies. Moreover, existing reviews of LCA in the nuclear sector (Warner and Heath 2012; Nian et al. 2014; Lenzen 2008) often do not include sections on waste processing.

One major finding of this review is that, in the studies identified, only two studies explicitly mentioned specific processing options as described in Table 3. Firstly, Guidi et al. (2010) considered the decontamination of a surface through the use

of a peelable gel, concluding that the conditioning, storage and disposal of the waste were the most dominant impacts of the decontamination process. Secondly, Wallbridge et al. (2013) explicitly described basic decontamination methods: washing with water, detergents or alcohol and 'more aggressive decontamination' such as blasting or treatment with chemicals are present within the scope of the LCA. However, in the LCA model produced by that study, these processes were simplified, for instance through the inclusion of a generic 'soap' dataset as a substitute for chemical surfactants and the exclusion of mechanical decontamination processes such as shot blasting.

The overall lack of data resolution regarding waste processing options, however, should be addressed by future studies. As more NPPs come offline and the total volume of waste for Europe alone is estimated to be in the region of 3,600,000 m³ (European Commission 2019) by 2030, there should be a clear focus on ascertaining the impacts of not just a blanket policy of geological disposal, but also waste processing and pre-disposal options both developed and developing. Without such analyses, it is not possible for future decision-making in the policy, operations and R&D realms to enhance further the environmental sustainability of waste disposal and processing. Moreover, without greater attention to these life cycle stages in future LCAs, the current understanding of front-end dominance in the overall nuclear power life cycle (outlined in Sect. 'LCA results') is highly uncertain, which may itself influence policy and operational decisions.

In the absence of other specific waste processing information, an assumption of grouting in steel boxes at low loadings could serve as a conservative default approach, as in the case of Godsey (2019).

Papers of partial relevance

An LCA by Koltun et al. (2018) is partially relevant to this review due to its focus on theoretical Gen IV High-Temperature Gas Reactors (HGTR). It included front-end construction and materials, use, back-end and decommissioning and waste disposal as boundary conditions, with a functional unit of 1 MWh electricity generated, which is typical of most LCAs surrounding the nuclear fuel cycle. In line with other studies, commissioning and decommissioning cause most of the global warming potential (GWP) but the construction of waste repositories is also a significant contributor. Basic solid materials are included, but no specific waste disposal or pre-disposal processes are detailed.

Conclusion

The challenge of managing radioactive waste is large and complex, requiring the processing of millions of cubic metres of waste globally over the coming decades. The

waste types are varied, with numerous technologies being developed to aid in their processing, and the environmental impacts of these must not be overlooked. Consequently, this paper has systematically reviewed the literature for studies addressing the back-end of the nuclear fuel cycle from a life cycle assessment perspective.

Overall, this literature review has revealed a lack of LCA studies focused on the back-end of the nuclear fuel cycle. Of the limited nuclear-related studies discovered, the focus has predominantly been the full nuclear life cycle or power generation. Though decommissioning is covered in some of the studies reviewed, as it is not the sole focus, granularity of data is insufficient, and comparisons are difficult to draw. For example, of the 72 relevant papers identified, only two (Wallbridge et al. 2013) (Guidi et al. 2010) are focused on applying LCA to decommissioning processes. This lack of granularity means that there is limited information as to which decommissioning activities and waste processing methods are more negatively impacting the environment than others, or how they might be improved. Addressing these gaps in future LCA studies will allow the nuclear sector to drive targeted, strategic innovation towards more sustainable back-end processes.

Three key findings from this review give rise to three recommendations, as follows. Firstly, far more activity is needed in future to apply LCA to decommissioning and back-end processes, with goals, functional units and system boundaries that are decommissioning-specific: This is important for both the optimisation of legacy waste processing, which is of a significant volume, and for the development of more comprehensive LCAs of the full nuclear fuel cycle for current and future reactor designs. These back-end processes should be delineated as much as possible during data collection and analysis to improve granularity, enabling the identification of specific hotspots and the generation of more precise, useful findings.

Secondly, this review has established that, at the time of writing, the published literature includes few attempts to investigate the environmental impacts of novel treatment/conditioning technologies and those in development using LCA methods, with most prior work focusing on efficiencies and effectiveness of application into the current fuel cycle. As a result, environmental considerations are only being incorporated into the development of new technologies via the narrower perspective of site licensing and local regulation rather than via a more holistic, life cycle perspective. This is likely hindering the overall environmental sustainability of the sector and could be rectified by applying early-stage or anticipatory LCA techniques to guide technology development.

Thirdly, although there is evidence that a greater proportion of impacts during decommissioning may be associated with solid waste types compared to liquid, LCA

practitioners should also consider the impacts associated with liquid waste processing and disposal. The vast array of technologies available has made it difficult to conduct meaningful LCA to date. With further attempts to collect data on specific waste processing technologies, LCA could be used to provide valuable insight into the most environmentally favourable options within decision-making processes.

In conclusion, future research should be focused on the collection of more LCA data surrounding back-end nuclear processes. This requires the collection of mass and energy balance information associated with existing and candidate waste processing technologies, enabling the completion of LCA models which can then, in turn, feed into broader LCAs of whole back-end processes as well as full fuel cycle models. Data should be as granular as possible and focus on both solid and liquid waste types. Current state-of-the-art impact assessment methodologies should be adopted to provide a broad range of impacts, and new radiological impact methodologies such as UCrad should be explored further. This will allow LCA practitioners the opportunity to conduct meaningful comparisons between different waste processing/decommissioning scenarios through identification of hotspots. This will ultimately help inform the research agenda of those investigating novel technologies and will aid in the integration of LCA within the nuclear sector.

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Data availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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References

- Abdel Rahman RO, Ibrahim HA, Hung Y-T (2011) Liquid radioactive wastes treatment: a review. *Water* 3:551–565
- Abrahamsen-Mills L, Wareing A, Fowler L, Jarvis R, Norris S, Banford A (2021) Development of a multi criteria decision analysis framework for the assessment of integrated waste management options for irradiated graphite. *Nucl Eng Technol* 53:1224–1235
- Allensworth JR, Simpson MF, Yim MS, Phongikaroon S (2013) Investigation of fission product transport into zeolite-a for pyroprocessing waste minimization. *Nucl Technol* 181:337–348
- Arzoumanidis I, D'Eusanio M, Raggi A, Petti L (2020) Functional unit definition criteria in life cycle assessment and social life cycle assessment: a discussion. *Perspectives on social LCA*. Springer International Publishing, New York
- Azapagic A, Clift R, Perdan S, Dawsonera Perdan S, Clift R (2011) Sustainable development in practice : case studies for engineers and scientists. John Wiley & Sons Ltd, Hoboken
- Bart F, Cau-Di-coumes CL, Frizon F, Lorente S (2013) Cement-based materials for nuclear waste storage. Springer, New York
- Benedict RW, Solbrig C, Westphal B, Johnson TA, Li SX, Marsden K, Goff KM (2007) Pyroprocessing progress at Idaho national laboratory. In: GLOBAL 2007: advanced nuclear fuel cycles and systems 741–747
- Bourg S, Poinssot C, Geist A, Cassayre L, Rhodes C, Ekberg C (2012) Advanced reprocessing developments in Europe status on European projects ACSEPT and ACTINET-I3. *Procedia Chem* 7:166–171
- Calloway TB, Martino CJ, Jantzen CM, Wilmarth WR, Stone ME, Pierce RA, Josephs JE, Barnes CD, Daniel WE, Eibling RE, Choi AS, White TL, Crowley DA, Baich MA, Johnson JD, Vijayaraghavan K, Nikolov A, Wasan DT (2003) Radioactive waste evaporation: current methodologies employed for the development, design and operation of waste evaporators at the Savannah river site and Hanford waste treatment plant. In: 9th ASME international conference on radioactive waste management and environmental remediation Volumes 1, 2, and 3, 2003-01-01 2003. ASME
- Choppin GR, Rydberg J, Liljenzin J, Ekberg, C (2013) Radiochemistry & Nuclear Chemistry, 4th edition, AcademicPress, Amsterdam.
- Deckers J (2011) Incineration and plasma processes and technology for treatment and conditioning of radioactive waste. *Handbook of advanced radioactive waste conditioning technologies*. Elsevier, Amsterdam
- Ding N, Liu J, Yang J, Yang D (2017) Comparative life cycle assessment of regional electricity supplies in China. *Resour Conserv Recycl* 119:47–59
- U.S. DOE (2022) Best practices for life cycle assessment (LCA) of direct air capture with storage (DACs). In: U.S. Department of energy, O. O. F. E. A. C. M. (ed.)

- Drecier M (1995) Externality of energy nuclear energy, vol. 5, European commission (1995). Externality of energy nuclear energy, 5
- EC-JRC (2011) International reference life cycle data system (ILCD) handbook – General guide for life cycle assessment: provisions and action steps, Publications Office.
- ECOINVENT (2023) Ecoinvent v3.9.1. Switzerland
- EDF (2016) Hinkley Point C, Building Britain's Low-carbon Future. EDF
- European Commission (2019) Inventory of radioactive waste and spent fuel present in the community's territory and the future prospects. Report from the commission to the council and the european parliament, Brussels
- European Commission (2021) Environmental Footprints methods [Online]. Available: https://green-business.ec.europa.eu/environmental-footprint-methods_en#related-documents. Accessed 2024
- European Platform On LCA (2022) Environmental footprint reference packages [Online]. Directorate-general for communication. Available: <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml>. Accessed Aug 2023
- Frischknecht R, Braunschweig A, Hofstetter P, Suter P (2000) Human health damages due to ionising radiation in life cycle impact assessment. *Environ Impact Assess Rev* 20:159–189
- Fthenakis VM, Kim HC (2007) Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study. *Energy Policy* 35:2549–2557
- Gagnon L, Bélanger C, Uchiyama Y (2002) Life-cycle assessment of electricity generation options: the status of research in year 2001. *Energy Policy* 30:1267–1278
- Garamszeghy M (2011) Compaction processes and technology for treatment and conditioning of radioactive waste. Handbook of advanced radioactive waste conditioning technologies. Elsevier, New York
- HW Godbee (1973) Use of evaporation for the treatment of liquids in the nuclear industry. Oak Ridge National Laboratory
- GODSEY, K. (2019) Life cycle assessment of small modular reactors using us nuclear fuel cycle. Clemson University, Masters
- Goedkoop M, Spriensma R (2001) The eco-indicator 99: a damage oriented method for life cycle impact assessment. Third Edition ed
- Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Van Zelm R (2009) A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level. The Hague, Ministry of VROM. ReCiPe
- Guidi G, Cumo F, de Santoli L (2010) LCA of strippable coatings and of steam vacuum technology used for nuclear plants decontamination. *Clean Technol Environ Policy* 12:283–289
- Guinée JB, Lindeijer E (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Springer Science & Business Media, Berlin
- Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, de Schryver A, Humbert S, Laurent A (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int J Life Cycle Assess* 18:683–697
- Heath P (2017) Hot isostatic pressing can substantially reduce the volume of nuclear waste. Research Features
- Hirabayashi T, Kameo Y, Myodo M (2000) Application of a laser to decontamination and decommissioning of nuclear facilities at JAERI, SPIE
- Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, Hollander A, Zijp M, Van Zelm R (2016) ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and the endpoint level – Report 1: characterization. Bilthoven, The Netherlands: Dutch National Institute for Public Health and the Environment (RIVM)
- IAEA (1992) Design and operation of radioactive waste incineration facilities. International Atomic Energy Agency, Vienna
- IAEA (1993) Bituminization processes to condition radioactive wastes. International Atomic Energy Agency, Vienna
- IAEA (2002) Application of Ion exchange processes for the treatment of radioactive waste and management of spent ion exchangers. International Atomic Energy Agency, Vienna
- IAEA (2004) Application of membrane technologies for liquid radioactive waste processing. International Atomic Energy Agency, Vienna
- IAEA (2011) The nuclear fuel cycle
- IAEA (2021) Treatment and conditioning of nuclear waste [Online]. UK: IAEA
- IEA (2022) Nuclear - fuels and technology [Online]. Available: <https://www.iea.org/fuels-and-technologies/nuclear>
- IPOINT (2018) Life cycle impact assessment – which are the LCIA indicator sets most widely used by practitioners? [Online]. iPoint-systems gmbh Ludwig-Erhard-Str. 58 72760 Reutlingen Germany: iPoint-systems gmbh. Accessed Apr 2022 2022
- ISO 2006a. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework. In: ISO (ed.) 2 ed
- ISO (2006b) ISO 14044:2006. Environmental management - Life cycle assessment - requirements and guidelines. Geneva, Switzerland: International organisation for standardisation
- Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. *Int J Life Cycle Assess* 8:324–330
- KGM (2024) Eora database [Online]. Available: <https://www.worldmrio.com/>. Accessed Jul 2024
- Kim K, Kim K, Choi M, Son SH, Han JH (2012) Treatment of ion exchange resins used in nuclear power plants by super- and sub-critical water oxidation – a road to commercial plant from bench-scale facility. *Chem Eng J* 189–190:213–221
- Kim JH, Seo EA, Chung KDG, CW, (2021) Utilization of recycled cement powder as a solidifying agent for radioactive waste immobilization. *Constr Build Mater* 289:123126
- Koltun P, Tsykalo A, Novozhilov V (2018) Life cycle assessment of the new generation GT-MHR nuclear power plant. *Energies* 11:3452
- Kriven WM (2021) Geopolymers and geopolymer-derived composites. In: Pomeroy M (ed) Encyclopedia of materials: technical ceramics and glasses. Elsevier, Oxford
- Lee YE, Lee KJ, Lee BW (2000) Environmental assessment of nuclear power generation in Korea. *Prog Nucl Energy* 37:113–118
- Lenzen M (2008) Life cycle energy and greenhouse gas emissions of nuclear energy: a review. *Energy Convers Manag* 49:2178–2199
- Lewin RG, Harrison MT (2015) 15 - International developments in electrorefining technologies for pyrochemical processing of spent nuclear fuels. In: Taylor R (ed) Reprocessing and recycling of spent nuclear fuel. Oxford Woodhead Publishing, Sawston
- LTD., KAP (2024) Eora database [Online]. Available: <https://www.worldmrio.com/>
- Matsuda M, Nishi T, Tamada S, Kikuchi M, Kato H (1994) Pelletizing method for radioactive waste and solidification method for radioactive waste pellet
- Ministry Of Economic Affairs And Employment (2022a) Management of spent nuclear fuel and radioactive waste in finland. Helsinki: vnjulkaisumyyni.fi
- Ministry Of Economic Affairs And Employment (2022b) Spent nuclear fuel will be disposed of in Finland [Online]. Helsinki, Finland. Available: <https://tem.fi/en/spent-nuclear-fuel>
- Nian V, Chou SK, Su B, Baully J (2014) Life cycle analysis on carbon emissions from power generation – the nuclear energy example. *Appl Energy* 118:68–82
- Nuclear Decommissioning Authority. 2021. Timing of the magnox reactor decommissioning strategy [Online]. Available: <https://>

- www.gov.uk/government/case-studies/timing-of-the-magnox-reactor-decommissioning-strategy. Accessed Dec 2022
- Nuclear Decommissioning Authority (2023) UK radioactive waste inventory 2022 [Online]. Nuclear decommissioning authority. Available: <https://ukinventory.nda.gov.uk/the-2022-inventory/2022-uk-data/>. Accessed Oct 2023
- Nuclear Decommissioning Authority (2024) About Radioactive Waste [Online]. Nuclear Decommissioning Authority. Available: <https://ukinventory.nda.gov.uk/about-radioactive-waste/what-is-radioactivity/what-are-the-main-wastecategories/>. Accessed May 2024.
- OECD (2022) Green growth and sustainable development [Online]. Available: <https://www.oecd.org/greengrowth/>. Accessed Nov 2022
- Ojovan MI, Lee WE (2005) Chapter 16 - immobilisation of radioactive wastes in Bitumen. In: Ojovan MI, Lee WE (eds) An introduction to nuclear waste immobilisation. Elsevier, Amsterdam, Oxford
- Paulillo A, Clift R, Dodds JM, Milliken A, Lettieri PSJ, P, (2020) Radiological impacts in life cycle assessment. Part I: General framework and two practical methodologies. *Sci Total Environ* 708:135179
- Paulillo A, Dodds JM, Palethorpe SJ, Lettieri P (2021) Reprocessing vs direct disposal of used nuclear fuels: The environmental impacts of future scenarios for the UK. *Sustain Mater Technol* 28:e00278
- Poinssot C, Bourg S, Boullis B (2016) Improving the nuclear energy sustainability by decreasing its environmental footprint. Guidelines from life cycle assessment simulations. *Prog Nucl Energy* 92:234–241
- Pomponi F, Hart J (2021) The greenhouse gas emissions of nuclear energy – life cycle assessment of a European pressurised reactor. *Appl Energy* 290:116743
- Posiva 2021. Operating license application
- Reeb C, Pierlot C, Davy C, Lambertin D (2021) Incorporation of organic liquids into geopolymer materials - a review of processing, properties and applications. *Ceram Int* 47(6):7369–7385
- Rosenbaum RK, Hauschild MZ, Boulay A-M, Fantke P, Laurent A, Núñez M, Vieira M (2018) Life cycle impact assessment. In: Hauschild MZ, Olsen SI, Rosenbaum RK (eds) Life cycle assessment theory and practice gewerbestrasse. Springer, Cham
- Santoyo-Castelazo E, Gujba H, Azapagic A (2011) Life cycle assessment of electricity generation in Mexico. *Energy* 36:1488–1499
- Sheldon S, Hadian S, Zik O (2015) Beyond carbon: quantifying environmental externalities as energy for hydroelectric and nuclear power. *Energy* 84:36–44
- Siddiqui O, Dincer I (2017) Comparative assessment of the environmental impacts of nuclear, wind and hydro-electric power plants in Ontario: a life cycle assessment. *J Clean Prod* 164:848–860
- Simapro (2024) Simapro databases [Online]. Available: <https://support.simapro.com/s/article/Which-databases-are-included-in-SimaPro>. Accessed July 2024
- SKB (2021) The final repository SFR [Online]. Available: <https://www.skb.com/our-operations/sfr/>. Accessed 21 Apr 2021
- Thorpe CL, Neeway JJ, Pearce CI, Hand RJ, Fisher AJ, Walling SA, Hyatt NC, Kruger AA, Schweiger M, Kosson DS, Arendt CL, Marcial J, Corkhill CL (2021) Forty years of durability assessment of nuclear waste glass by standard methods. *Npj Mater Degrad* 5(1):61
- Turconi R, Boldrin A, Astrup T (2013) Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. *Renew Sustain Energy Rev* 28:555–565
- VGB Powertech EV (2012) Waste disposal for nuclear power plants. VGB PowerTech e.V, Germany
- Vira J (2017) Geological repository for high-level nuclear waste becoming reality in Finland. In: Geological repository systems for safe disposal of spent nuclear fuels and radioactive waste
- Wallbridge S, Banford A, Azapagic A (2013) Life cycle environmental impacts of decommissioning Magnox nuclear power plants in the UK. *Int J Life Cycle Assess* 18:990–1008
- Walling SA, Kauffmann MN, Gardner LJ, Bailey DJ, Stennett MC, Corkhill CL, Hyatt NC (2021) Characterisation and disposability assessment of multi-waste stream in-container vitrified products for higher activity radioactive waste. *J Hazard Mater* 401:123764
- Warner ES, Heath GA (2012) Life cycle greenhouse gas emissions of nuclear electricity generation. *J Ind Ecol* 16:S73–S92
- WILLE, H. 1987. System decontamination with cord and decontamination for unrestricted release. Nuclear Power Performance and Safety. Vienna: IAEA
- World Nuclear Association (2021) Decommissioning nuclear facilities [Online]. Accessed April 2022 2022
- Yamamoto S, Takahashi H, Taniguchi H, Kawashima A, Takahashi H, Kikura H (2020) Fundamental study on decontamination method using shot blasting and barrel polishing for radioactive metal waste. In: 2020 international conference on nuclear engineering collocated with the ASME 2020 power conference, V001T04A014

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