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Life Cycle Assessment of an upcoming Nuclear Power Plant Decommissioning: the Fessenheim case study from public data --Manuscript Draft--

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	Interreg Upper Rhine 2021-2027 (A1.3)	Not applicable
Abstract:	<p>Purpose Historical French fleet of Nuclear Power Plants (NPP) is near end-of-life, with 14 NPPs planned to begin decommissioning by 2035. Despite decade-old calls for more research regarding these activities' environmental impact, very few if any studies were conducted since. Due to the French fleet high-degree of standardization, a prospective investigation regarding the Fessenheim NPP – first large-scale plant to be decommissioned in France, starting 2026 – is conducted to identify results of interest beyond this case study.</p> <p>Methods A life cycle assessment is realized, following ISO 14040/44, with a functional unit defined as “the decommissioning of the Fessenheim NPP”. The system boundaries encompass four unit-processes: Dismantling of electromechanical equipment, Clean-up of the structures, Demolition of plant buildings and Transport of conventional and radioactive waste (RW). This last unit-process is investigated separately to make a clear comparison of conventional and radioactive waste. Pre-decommissioning activities, Soil rehabilitation and RW final storage are excluded. Primary data was obtained from the decommissioning public report of EDF (Electricity of France), with scaling based on the literature and third-party reports/documents. Background processes were modelled with the ecoinvent 3.8 database. Environmental impacts are estimated using the CML-IA baseline methodology to allow comparison with previous works based on CML2001.</p> <p>Results and discussion The “Metal cutting” sub-process is found to be the major contributor to environmental impacts during Dismantling, Clean-up and Demolition, results varying from 62.6 to 99.5% depending on the impact category. A sensitivity analysis explores the effect of variation in shares of thermal and mechanical cutting. It demonstrates the huge potential of impact reduction for the total system under study, if</p>	

thermal cutting use is limited as much as possible. Despite representing only 5% of the total mass of waste, RW scores 1.8-6.6 times higher than conventional waste during Transport, due to much higher distances to cover and specific conditioning. Previous explorations of results transferability are found to be methodologically uncertain, and the NPP total power installed is evaluated as an unpromising transferability factor. Conclusions Decommissioning of nuclear power plants is still in need of thorough studies based on exhaustive and transparent datasets. Until then, state-of-the art prospective assessments and transferability of LCA results to future studies is severely limited. Restraint in use of oxy-acetylene cutting is nevertheless highly recommended. French unique policy regarding very low-level waste needs further consideration, and decentralized storage sites is a promising research lead.

Response to Reviewers:

Dear Dr. G. Mondello,

We thank you and the reviewers for your time.
Please find our responses to the minor revisions asked below.
These responses are also available in word format in the attached files.

General note: All manuscript modifications are highlighted in yellow in the revised manuscript and supplementary information files. To help the final editing process, we also added the PDF version of the figures. They come in both black & white and colorized versions, which we respectively recommend for the print and online versions. MSOffice pptx. original versions can be sent if the editor needs them.

Reviewer 1 comments:

- The use of "tons" instead of "tonnes" is noted. It would be beneficial if the authors could provide clarification on this matter. As a point of reference, a ton is an imperial unit equivalent to 1,016.047 kg or 2,240 lbs, while a tonne is a metric unit equivalent to 1,000 kg or 2,204.6 lbs.

Authors response to the comment above:

- There was indeed a systematic typo when writing the unit full name. The manuscript and supplementary information have been corrected to metric tonnes (this has no incidence on the numerical values which were "tonnes" already).

Reviewer 1 comments:

- I suggest the inclusion of the complete life cycle inventory (LCI) with references to the database (and datasets) used for representing background processes, possibly in supplementary materials. Additionally, specifying the type of secondary data collected (e.g., reference, calculated, or scaled) would enhance transparency and allow readers to delve deeper into the data sources.

Authors response to the comment above:

- A new section called "5. Database references" has been added in the supplementary information.
- The added Tables S18-S19-S20-S21 of this "Database references" section compile the input quantities, indexed by processes and sub-processes, with the appropriate ecoinvent reference, and a dedicated "Data construction" column specifying all operations that allowed to construct each numerical value with references.

Reviewer 1 comments:

- Furthermore, I recommend exploring options to consolidate the three tables presented in Table 6 to avoid potential confusion during the paper's publication.

Authors response to the comment above:

- The three sub-tables have been consolidated into a single Table 6 in the manuscript.

Reviewer 1 comments:

- In addition, the conclusion could benefit from the addition of additional considerations on future studies.

Authors response to the comment above:

- More detailed developments have been made on expected future studies in the first paragraph of the conclusion, regarding prospective LCA and radiological impacts on human health.

Best regards,

Dr. G. Quaranta

Revision for:

Life Cycle Assessment of an upcoming Nuclear Power Plant Decommissioning: the Fessenheim case study from public data

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General note: All manuscript modifications are highlighted in **yellow** in the revised manuscript and supplementary information files. To help the final editing process, we also added the PDF version of the figures. They come in both black & white and colorized versions, which we respectively recommend for the print and online versions. MSOffice pptx. original versions can be sent if the editor needs them.

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- In addition, the conclusion could benefit from the addition of additional considerations on future studies.	- More detailed developments have been made on expected future studies in the first paragraph of the conclusion, regarding prospective LCA and radiological impacts on human health.

[Click here to view linked References](#)

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Keywords: Environmental Impact, Life Cycle Assessment, Decommissioning, Fessenheim Nuclear Power Plant

Authors contribution

Conceptualization, M.K. and G.Q.; Methodology, M.I., M.K. and G.Q.; Data curation, M.I. and P.R.; Investigation, M.I., P.R., M.B. and G.Q.; Formal analysis, M.I. and P.R.; Funding acquisition, G.Q.; Resources, M.K. and G.Q.; Software, M.K. and G.Q.; Validation, P.R., M.K., M.B. and G.Q.; Visualization, M.I. and P.R.; Writing—original draft, M.I.; Writing—review and editing, M.I., P.R., M.B. and G.Q.; Supervision, M.K. and G.Q.; Project administration, M.K. and G.Q. All authors have read and agreed to the published version of the manuscript.

Abstract

Purpose Historical French fleet of Nuclear Power Plants (NPP) is near end-of-life, with 14 NPPs planned to begin decommissioning by 2035. Despite decade-old calls for more research regarding these activities' environmental impact, very few if any studies were conducted since. Due to the French fleet high-degree of standardization, a prospective investigation regarding the Fessenheim NPP – first large-scale plant to be decommissioned in France, starting 2026 – is conducted to identify results of interest beyond this case study.

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Results and discussion The “Metal cutting” sub-process is found to be the major contributor to environmental impacts during Dismantling, Clean-up and Demolition, results varying from 62.6 to 99.5% depending on the impact category. A sensitivity analysis explores the effect of variation in shares of thermal and mechanical cutting. It demonstrates the huge potential of impact reduction for the total system under study, if thermal cutting use is limited as much as possible. Despite representing only 5% of the total mass of waste, RW scores 1.8-6.6 times higher than conventional waste during Transport, due to much higher distances to cover and specific conditioning. Previous explorations of results transferability are found to be methodologically uncertain, and the NPP total power installed is evaluated as an unpromising transferability factor.

Conclusions Decommissioning of nuclear power plants is still in need of thorough studies based on exhaustive and transparent datasets. Until then, state-of-the art prospective assessments and transferability of LCA results to future studies is severely limited. Restraint in use of oxy-acetylene cutting is nevertheless highly recommended. French unique policy regarding very low-level waste needs further consideration, and decentralized storage sites is a promising research lead.

1. Introduction

According to the International Energy Agency, nuclear energy is today's second largest source of low emissions (*i.e.* non-fossil-based) power generation, after hydropower (IEA 2022). In 2020, nuclear power made up about 10% of global electricity production. However, nuclear power is historically an energy production mode subject to controversy fuelled by antagonist cultural types of rationalities (van de Graaff 2016). Several countries decided to phase out nuclear power and not construct nuclear power plants (NPPs) in the future. This decision was reinforced following the Fukushima Daiichi Nuclear Power Plant accident in Japan in 2011. Besides, a growing number of nuclear facilities are reaching the end of their operational lifetimes. In 2019, more than 60% of world's operational reactors are older than 30 years, which means that in the foreseeable future, many NPPs will be decommissioned. The expected market volume of nuclear reactors in decommissioning is expected to grow from 25 GW in 2019 to 75–85 GW(e) until the mid-2030s. In the next decade, the main decommissioning markets are the USA, Japan, and Germany with a capacity reduction of 131.5 GW until 2047. At the same time, many new nuclear reactors (54 at the end of 2019) are under construction in several countries, for example, in China and India (11 and 6 reactors, respectively) (US Nuclear Regulatory Commission 2022).

In this context, the three-countries region of the Upper Rhine, which extends across France, Germany and Switzerland is emerging as a cross-border region subject to an almost simultaneous decommissioning process for several NPPs. The last nuclear power plant in Baden-Württemberg (Germany), Neckarwestheim was recently permanently shut down (April 2023). Switzerland voted in 2017 in favour of an exit from nuclear power. In France, on September 26, 2019, the Secretary of State to the Minister of Ecological and Solidarity Transition announced the closure of the first reactor of the Fessenheim power plant in February 2020 and the second one in June 2020. The Fessenheim plant closure induces important ecological, economic and social changes in the area around the power plant and is located in a highly industrialized region. This makes it a unique object to study and resulted in the creation of the Human-Environment Observatory (OHM) Fessenheim in 2018 (OHM Fessenheim 2018). Moreover, in France, 56 reactors of the NPP fleet in operation are all pressurized water reactors (PWRs) with similar design (IAEA 2022). The decommissioning of the Fessenheim NPP could then be as a “laboratory” for the reactors to be shut down in the coming years.

Three decommissioning strategies have been defined by the International Atomic Energy Agency (IAEA), namely immediate decommissioning, deferred decommissioning and entombment (IAEA 2002). Immediate decommissioning allows the removal or decontamination of the nuclear facility, equipment, structures and parts of the facility containing radioactive contaminants shortly after closure; at a level that allows release of ownership and termination of the Nuclear Regulatory Commission (NRC) license. In deferred decommissioning, a nuclear facility is maintained and monitored in a condition that allows radioactivity to decrease; then the plant's equipment is dismantled and the property decontaminated. For the entombment strategy, radioactive contaminants are permanently encased on site in structurally sound material such as concrete. The facility is maintained and monitored until the radioactivity decays to a level permitting restricted release of the property (US Nuclear Regulatory Commission 2022). In France, immediate decommissioning is a major national principle of the nuclear decommissioning and waste treatment policy.

91 However, regardless of the chosen decommissioning strategy, there is an increased need for the
1 92 acquisition of multidisciplinary knowledge that considers different changes and factors associated with NPP
2 93 decommissioning (Siddiqui and Dincer 2017; ANDRA 2018; EDF 2020; Park et al. 2022). Specific focus should
3 94 be put on economic issues, such as problems of jobs and/or financial losses for local authorities. Particular attention
4 95 should be also paid to the global public, local residents, and operating company's perception of the risk incurred
5 96 during the decommissioning steps. Of course, decommissioning should be considered from an environmental
6 97 perspective because it is a time and energy-intensive process which includes energy use, various emissions and
7 98 wastes. To evaluate environmental impacts caused by decommissioning, such as Global Warming, Terrestrial
8 99 Ecotoxicity, and Aquatic Ecotoxicity, the Life Cycle Assessment (LCA) procedure can be used. LCA is a method
9 100 for assessing the environmental impacts of a system from the extraction of raw materials to the processing and
10 101 final disposal of wastes (ISO 2006a, b). This tool breaks down the industrial system studied into elementary
11 102 processes such as: the construction, use and end of life of the system. The inputs/outputs of these elementary
12 103 processes are quantified and associated to environmental impacts.

19
20 104 The environmental performance of NPPs has previously been evaluated by LCA in different countries,
21 105 namely Germany (Seier and Zimmermann 2014), Canada (Siddiqui and Dincer 2017) and Australia (Lenzen 2008;
22 106 Koltun et al. 2018). Most of the studies focused on the construction and operation phase of the NPP life cycle
23 107 and/or on the quantification of the greenhouse gas (GHG) emissions, energy consumption, waste management and
24 108 transport-related impacts during the end-of-life phase of the system. However, very few studies made a specific
25 109 focus on the environmental impacts generated by the decommissioning phase of NPPs (Wallbridge et al. 2013;
26 110 Seier and Zimmermann 2014). The first LCA study was produced by Wallbridge *et al.* (2013) who reported the
27 111 decommissioning process of the Trawsfynydd NPP in Wales (UK). The system boundaries considered all stages
28 112 in the life cycle of decommissioning, including site management, waste retrieval, plant deconstruction, packaging
29 113 and storage of intermediate- (ILW) and low-level wastes (LLW). The environmental impacts were estimated using
30 114 the CML2001 methodology. Primary data was sourced from the Trawsfynydd site and the background from
31 115 ecoinvent database. Global Warming Potential (GWP) was estimated at 241 kt CO₂ eq./functional unit, or 3.5 g
32 116 CO₂ eq./kWh of electricity generated during the lifetime of the plant, 55% of the impact coming from plant
33 117 deconstruction and 30% from ILW disposal. Seier and Zimmermann (2014) examined the environmental impacts
34 118 of the ongoing decommissioning of the NPP in Lubmin (Germany). The system boundaries included removal and
35 119 demolition of plant components and buildings, as well as decontamination, conditioning, interim storage and final
36 120 repository of LLW and ILW, disposal and recycling of conventional waste. The GaBi software (with GaBi,
37 121 ecoinvent, and ProBas databases) was used to model background processes. Environmental impacts were
38 122 estimated using the CML2001 methodology. Total GHG emissions reported were 1,651,265 t CO₂ eq. (11.27 g
39 123 CO₂ eq./kWh). Siddiqui and Dincer (2017) analyzed, assessed and compared the environmental impacts of nuclear,
40 124 wind and hydropower generation in the province of Ontario (Canada) using the LCA approach. The upstream,
41 125 operation, decommissioning and downstream phases of these power generation methods were included. Five
42 126 environmental impact categories defined by CML2001 were considered. The authors concluded that the
43 127 decommissioning phase may have a substantial contribution to various environmental impacts: Acidification
44 128 (49%), Human Toxicity (48%) and Photochemical Ozone Creation Potentials (46%). The most recent research
45 129 (Er-Raki et al. 2019; Er-Raki 2021) studied the dynamic assessment of environmental impacts in industrial context,
46 130 especially scenarios of energy transition. The impact assessment was carried out using the SimaPro software, the

131 ILCD 2011 method and the ecoinvent database. The author found that for the French NPP fleet, the associated
1 132 impact occurs mainly during the production and decommissioning phase, 4.3 and 3.7 CO₂ eq./kWh, respectively
2
3 133 – total being 8.62 g CO₂ eq./kWh when adding construction phase (Er-Raki 2021).

4
5 134 In this work, we aim to assess the potential environmental impacts occurring in the incoming decommissioning
6 135 process of the Fessenheim NPP, using the life-cycle assessment methodology. We will further analyze the
7
8 136 activities contributing to the sub-processes of the studied system. To our knowledge, this level of detail was not
9 137 reached in any previous work.

10
11 138 The principles, requirements and methods of LCA are defined by ISO standards 14040 and 14044, 2006 (ISO
12 139 2006a, b). LCA is carried out in four stages: definition of the objectives and scope of the study, inventory analysis,
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14 140 impact assessment and interpretation of the results.
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2. General Presentation of the Fessenheim NNP

The Fessenheim NPP is located on the Rhine River, 1.5 km from the German border and about 30 km from Switzerland (Figure 1a). Commissioned on 30 December 1977 and 18 March 1978, the NPP is composed of two 900 MW pressurized water reactors. The nuclear installation is connected to the Muhlbach Power Station distributing electricity to the grid and covers an area of ~36 ha with nuclear and conventional buildings (Figure 1b). The power plant is thus composed of two reactor buildings (BR), two fuel buildings (BK), annex buildings (BW), one nuclear auxiliary building (BAN) and one electrical building with two control rooms which are common to both units (Figure 1c). The NPP produced a total of 447.3 TWh until its closure June 30, 2020.

3. Goal and scope of this study

3.1. Objective

The present study attempts to perform prospective modelling and evaluate the environmental impacts during decommissioning phase of the Fessenheim NPP. More especially, the purpose of the LCA is to identify the activities of decommissioning that have the highest environmental impact and their mitigation potentials. CML-IA baseline V3.08 has been selected as Life Cycle Impact Assessment (LCIA) method for this work, in order to allow comparison of LCIA results with the previous studies, who used the CML2001 method (Wallbridge et al. 2013; Seier and Zimmermann 2014). CML-IA baseline V3.08 allows to assess eleven different mid-point impact categories, and special attention is paid to the assessment of the following five impact categories: Abiotic Depletion Fossil Fuels (AD FF), Terrestrial Ecotoxicity (TE), Freshwater Ecotoxicity (FWAE), Global Warming (GW) and Human Toxicity (HT).

To date, the scientific community paid much attention to the environmental impact studies on GW in the case of NPP due to the emissions generated by the building deconstruction, and of course due to the general interest of the public and policy makers regarding this impact category (IPCC 2023). Following the same logic, we add AD FF due to the public and scientific interest of natural resources management (Frankel 2012), and the specificity of the French Energy mix, with its electricity production including nuclear energy, then fossil energy and renewable energy in lower percentages. For a new land occupation, a soil diagnosis is necessary to optimize the remediation technic and knowledge of TE is thus essential for the implementation of the best remediation technic (Mirguet 2023). FWAE is considered due to possible discharges into the water of the Grand Canal of Alsace and the Rhine River. Finally, HT must also be evaluated, typically because of the inorganic compounds that can affect the respiratory tract during NPP demolition, an element of scientific and general public interest (Tränkler et al. 1996; Roussat et al. 2008; Butera et al. 2015). The Ionizing Radiation category, which could have been available by using the non-baseline version of CML IA, was not considered for two reasons. Firstly, 99.9% of radioactivity will have been removed by pre-decommissioning operations (EDF 2020) and, secondly, no data on radioactive effluents generated by the decommissioning were available at the time of this study.

The results of this work are expected to help stakeholders identify the stages of the decommissioning process where improvements can be made.

3.2. Functional unit

One of the key questions is the choice of the functional unit (FU). According to ISO 14040, the FU is "a quantified performance of a product system intended to be used as a unit of reference in a life cycle assessment". This functional unit defines the object of the study. All subsequent analyses, therefore, depend on this functional unit because all inputs and outputs of the Life Cycle Inventory (LCI) are related to the functional unit (ISO 2006a, b). The previous LCA studies defined the FU as the decommissioning of NPP normalised by the number of kWh produced during the operational phase. It was found in the two publications dealing only with decommissioning that the functional unit used is "decommissioning of a nuclear plant" (Wallbridge et al. 2013; Seier and Zimmermann 2014). "Decommissioning of a nuclear power plant" FU seems to be more coherent with the objectives of this type of study. However, to preserve the perspective of other studies, the authors give a conversion

187 in 1 kWh related to the amount of energy produced by the NPP, warning that this normalization creates a bias
188 related to the operation lifetime of the NPP. In this study, the chosen functional unit is "Fessenheim NPP
189 decommissioning".

190 3.3. System Boundaries

191 As was mentioned in the Introduction part, immediate decommissioning and removal of all radioactive material
192 was decided for the Fessenheim NPP, *i.e.* the time between final shutdown and the first decommissioning
193 operations will be as short as possible. This pre-Decommissioning time includes drainage and decontamination of
194 systems, removal of waste and chemical products, preparation of spaces for processing of future waste from
195 decommissioning, etc. The spent fuel from reactor 1 was completely removed in 2021. The removal of spent fuel
196 from reactor 2 should have been completed in 2023. EDF currently plans to obtain the authorization decree in 2025
197 to start decommissioning in 2026.

198 The system boundaries and the elementary processes are based on the public report provided by EDF (2020).
199 Figure 2 illustrates the system boundaries of the so-called "Fessenheim NPP Decommissioning" in this study,
200 which includes four elementary processes: Dismantling of the electromechanical equipment, Clean-up of internal
201 structures, Demolition of buildings and the Transport of conventional waste and radioactive waste (RW) to
202 disposal. We decided to not consider other steps of the decommissioning process, such as remediation (ground and
203 groundwater), repair/maintenance for decommissioning and waste treatment (recycling).

204 3.3.1. Dismantling of electromechanical equipment

205 This step aims to reduce the size of components that were activated and/or contaminated so that they can be
206 removed more easily and placed in waste containers. First, the components no longer needed for decommissioning
207 operations will be removed. In the reactor building, the permanent removal of the primary system is followed by
208 the cutting of the reactor pressure vessel. The components and equipment in the other buildings, namely in the
209 nuclear fuel building, and nuclear auxiliary building are also to dismantle and remove. Only the materials necessary
210 for carrying out the decontamination work in the Clean-up step are left in place (EDF 2020).

211 Some of this work must be carried out remotely or under water to protect workers and prevent any leakage of
212 radioactivity. Various mechanical cutting techniques (shears, saws, diamond wire, high-pressure water jet) as well
213 as thermal cutting techniques using torches and lasers can be used (Rohde 2008; Laraia 2012).

214 3.3.2. Clean-up of nuclear structures

215 The Clean-up of internal structures (concrete, metallic elements), systems and components will be realized after
216 Dismantling of electromechanical equipment in the nuclear buildings. This step includes metal cutting,
217 decontamination of internal structures and RW conditioning.

218 The decontamination sub-process involves the complete or partial removal of radioactive substances/material from
219 surfaces or within a system/item by different techniques (simple washing, mechanical or chemical action, etc.)
220 (EDF 2020). The selection of technologies depends on different factors such as the type of radioisotopes, the
221 activity level, etc. In the Fessenheim NPP case, decontamination during pre-decommissioning aims to reduce the
222 dose rate around the concerned components and the risk of contamination spread. However, decontamination can

223 still be needed during decommissioning to change the waste category for the disposal of the component, to increase
224 the potential for recycling and reusing and to reduce the dose rate during further waste handling.

225 3.3.3. Demolition of buildings

226 For conventional buildings, the “Demolition” step can take place as soon as they no longer have any use for
227 decommissioning activities. For nuclear buildings, it can only begin once the structures have been cleaned up and
228 then released. After Demolition of building foundations, backfill made up of rubble from the Demolition itself is
229 realized (EDF 2020).

230 3.3.4. Transport of RW and conventional wastes

231 The decommissioning of the Fessenheim NPP will produce about 405,000 tonnes of waste in total. EDF predicts
232 that 95% of these will be non-radioactive waste, known as conventional waste (*e.g.*, concrete and metals). It should
233 be noted that EDF's intention is to recover a minimum of 90% (in mass) of conventional waste through recycling
234 and reuse (EDF 2020). Furthermore, Fessenheim NPP decommissioning will produce around 5% of radioactive
235 waste, amounting to 18,400 tonnes. The composition of the RW is as follows: 3% (12,000 tonnes) very low-level
236 waste (VLLW); 2% (6,200 tonnes) low- or intermediate-level short-lived waste (LILW-SL); 0.1% (200 tonnes)
237 intermediate-level long-lived waste (ILW-LL). It should be noted that decommissioning does not generate high-
238 level waste (HLW). RW are subject to different sorting, conditioning and storage conditions depending on their
239 level of radioactivity.

240 Each category of radioactive waste has its specific storage site in France. Two are directly managed by ANDRA
241 (National Agency for Radioactive Waste Management): VLLW are stored in CIRES (Industrial consolidation,
242 storage and disposal center) at Morvillier in Aube department, and LILW-SL in CSA (Aube Storage Center) at
243 Soulaines-Dhuys, also in Aube. ILW-LL are temporarily stored in the ICEDA (Packaging and storage facility for
244 activated waste) managed by EDF at Bugey, in Ain department. Figure 3 provides a visualization of their respective
245 locations relative to the Fessenheim NPP. The “Transport” step will require use of trucks and trains to transfer the
246 RW to their different destination (see Inventory analysis).

4. Inventory Analysis

4.1. Data origin and uncertainties

Conducting a representative LCA requires to collect material and energy inputs that occurs in each defined elementary process. However, at the time of this study, EDF did not publicly disclose projections on the amount of energy and material needed for this NPP decommissioning project. In addition to this, the prospective nature of this research necessarily leads to a lack of data.

The public decommissioning report of EDF constitutes our primary data source (EDF 2020), however this document does not provide detailed information on the techniques which will be used during Dismantling, Clean-up and Demolition. In addition, data on material and energy inputs are scarce. Moreover, there is a limited number of studies on this topic, and datasets are specific to each NPP. Therefore, applying them to the Fessenheim decommissioning project requires scaling. We then compiled publicly available data in the scientific literature (from previous decommissioning studies or on related processes), feedback reports, and official documents, namely from EDF/ANDRA (Table 1). The gathered information was articulated to various hypotheses (detailed with related calculations in the supplementary materials) to build the LCI database applied to the Fessenheim NPP decommissioning. Typical examples are the “Metal cutting” and “Decontamination” sub-processes, where we followed the approach of previous work (Seier and Zimmermann 2014) to adapt the data from (Rohde 2008) to the available material data of the Fessenheim NPP. By doing so, we give a penalising estimate of the potential impacts that can be quantified by sensitivity analysis. We will show that these exploratory results allow to define a range of results for our system scope which highlights the importance of a detailed contribution analysis. Hence, the importance, for future studies, of precise data on the repartition of processes actually employed.

Main inventory data related to our study system were calculated on the basis of the work of Seier and Zimmerman (2014) and Rohde (2008) and scaled to the functional unit of the system studied. In the following sub-sections, we will give an overview description of the different processes, general explanations and synthetic tables summarizing the required inputs. Detailed hypotheses and calculations are described in the supplementary information (S1).

4.2. Dismantling

During the “Dismantling” step, EDF will dispose of the different electromechanical equipment, to only keep building structures and equipment needed for the “Clean-up” step. The Dismantling unit process is thus modelled by three elements: “Electromechanical (Metal cutting)” and “Deconstruction (concrete)”, which corresponds to the activities transforming equipment and their specific infrastructure into manageable pieces for conditioning; and “RW conditioning”, which models the activity of mortar casting necessary to handle the radioactive waste (Table 2).

The EDF (2020) report does not provide precise information on the specifics of the Metal cutting sub-process. However, the quantity of metallic radioactive waste in the Dismantling step is given (S1-1.1). The Rohde (2008) report was thus used to determine the quantities of oxygen, acetylene, hydrogen and argon needed for metal cutting. A scaling designed from this previous work was needed. However, Rohde (2008) gives the amount of material as a number of “bottles” consumed per year, associated to the mass of waste cut per year. To have a precise quantity

283 of material, we assumed a volume of 10 m³ in a material bottle. The ideal gas law ($PV = nRT$), was then used to
284 obtain a quantification in tonnes, in order to implement these inputs into the LCA software SIMAPRO® (S1-1.2).

285 The mass of concrete radioactive waste during the Dismantling stage is also provided by the EDF report (S1-1.1).
286 Lünser (1998) and Seier and Zimmermann (2014) reported that 4.82 L of diesel per tonne of concrete are required
287 for the demolition of concrete. This value was thus related to the quantity of concrete issued during the Dismantling
288 step (S1-1.3).

289 ANDRA (2018) explains that the conditioning of radioactive waste from the NPPs must be established by the
290 producers. A package of LILW-SL radioactive waste must be conditioned with 80% of its mass in mortar (cement
291 coating material). ILW-LL is packaged with a steel vessel and a CASTOR train carriage. VLLW waste does not
292 require any special conditioning for transport (ANDRA 2018). These specifications were applied to the mass of
293 RW given by EDF in their report (S1-1.4).

4.3. Clean-up

295 The “Clean-up” unit process corresponds to activities applied for nuclear buildings, where the potential
296 contamination of structures needs to be assessed and then eliminated. The Clean-up unit process is thus composed
297 of three elements: “Metal cutting”, “Decontamination” and “RW conditioning” (Table 3).

298 Based on the EDF (2020) report predicted mass of metallic waste for the Clean-up step (S1-2.1), “Metal cutting”
299 is modelled in the same way as in Dismantling step (S1-2.2). “Decontamination” corresponds to the material input
300 that is needed to treat radioactive materials to make them less hazardous. To overcome the lack of data related to
301 this sub-process in the EDF (2020) report, a scaling designed from previous work was again needed. Data from
302 Rohde (2008) was retrieved to construct transposition coefficients (S1-2.3) which were applied to the quantity of
303 concrete and metallic RW predicted for the Fessenheim NPP Clean-up step. The materials used are water (concrete
304 and metallic waste), steel gravel, phosphorous acid and oxalic acid (metallic waste only).

305 The Clean-up step does not produce so-called “ILW-LL” waste. The EDF (2020) report provides the quantity of
306 RW produced during these operations, and the quantity of mortar needed was calculated according to the ANDRA
307 conditioning methods explained in the previous section (S1-2.4).

4.4. Demolition

309 The “Demolition” step is partly synchronized with the Dismantling and Decontamination steps, as these two
310 processes must have been completed in order to proceed with Demolition, in the case of nuclear buildings.
311 However, conventional buildings can and will be demolished as soon as they have no use for the decommissioning
312 operations. This step is then modelled in two sub-processes (Table 4).

313 “Deconstruction (general)” corresponds to standard building and piping demolition activities. The use of diesel is
314 calculated in the same way as for “Deconstruction (concrete)” during Dismantling step (S1-3.3). The value of 4.82
315 L per tonne of concrete is thus transposed to the mass of expected conventional concrete waste. However,
316 proportions of the different kinds of conventional waste are not specified in the EDF (2020) report. This mass of
317 concrete was estimated by transposing waste proportions determined by Koltun *et al.* (2018) to the total value of
318 conventional waste reported by EDF (S1-3.1). Moreover, building demolition modelling also needs to account for

319 an electricity consumption caused by supplementary activity related to metal framework for buildings, as estimated
1 320 by Bozdag (2007). The determined amount is 11 kWh/m² to demolish a building. To calculate the total energy
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3 321 value for the case of the Fessenheim NPP, the area of the buildings must be known. Open Street Map was then
4 322 employed to estimate the 2D surface and the buildings heights has been quantified (personal estimation). Different
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6 323 calculations allowed to evaluate the surface of the walls and floors of the buildings (S1-3.4).

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8 324 Another “Metal cutting” sub-process, identical as in previous modelling, allows to account for the necessary
9 325 preparation of conventional metal waste to proceed to their evacuation to the “Cernay Environment – Alsadis”
10 326 recycling plant. Estimated proportions of Koltun *et al.* (2018) were also applied to the total mass of conventional
11 327 waste from Fessenheim NPP in order to quantify conventional metal waste. As in Dismantling and Clean-up steps,
12 328 data from Rhodes (2018) were used to transpose the amount of material needed to cut the mass of the predicted
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14 329 metal waste (S1-3.2).

17 18 330 4.5. Transport

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20 331 In previous studies, Wallbridge *et al.* (2013) and Seier and Zimmerman (2014) modelled the transportation of
21 332 conventional and radioactive waste produced by NPP decommissioning separately. Indeed, their intention was to
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23 333 account for the difference in environmental impacts caused by the distinct final disposal solutions. In this work,
24 334 although we do not take into account the specific impact of the final disposal steps, “Transport” of conventional
25 335 and RW waste are also treated separately to allow for comparison of these two categories of waste (Table 5). This
26 336 is especially important when taking into consideration the unique French situation regarding VLLW, which are
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28 337 currently all transported to a final storage site, in the absence of a legal release threshold.

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31 338 Transport of conventional waste is done by road. EDF emphasizes its policy on waste recovery (recycling). The
32 339 Fessenheim NPP has an expected recycling rate of 90.4% (EDF, 2020). For this reason, the transfer of waste must
33 340 then be done in a waste treatment center with an adapted recycling capacity. The nearest center is 42 km from the
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35 341 NPP (OpenStreetMap), at the treatment center "Cernay Environnement - Alsadis" (S1-4.1).

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37
38 342 According to the regulations of ANDRA, most of radioactive waste is transported by road. VLLW goes to CIRES
39 343 (317 km from the NPP) and LLW goes to CSA (314 km). In the case of ILW-LL, transfer by rail to ICEDA (395
40 344 km) is allowed. As railway infrastructure exists at Fessenheim NPP, transfer of all ILW-LL by railway was
41 345 considered very likely (S1-4.2). To calculate the distance required for trucks, OpenStreetMap was once again used.
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43 346 However, for rail transport, OpenRailwayMap was employed to calculate the required distances. This website also
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45 347 allowed to locate electrified and non-electrified railroads, the latter for which diesel is the energy vector consumed.

5. LCIA Results

5.1. Overall comparison

In the following section, the Transport process has been studied individually in order to allow a clear comparison in environmental impacts of conventional and RW waste pathway to disposal. The total impact of the other decommissioning processes (Dismantling, Clean-up, and Demolition) is laid out in Figure 4. This preliminary comparison shows that the Demolition process has noticeably the most significant impact on every LCIA categories analysed (85.1% to 87.8%) and the Dismantling process scores as the second most significant process (11.5% to 13.4%), Clean-up being relatively marginal (0% to 2.3%).

As explained in the objectives and scope of the study, five midpoint categories were subjected to further analysis: Abiotic depletion (Fossil fuels), Global Warming, Fresh water aquatic ecotoxicity, Human toxicity, Terrestrial ecotoxicity.

5.2. Sub-processes contribution analysis

The breakdown of the different sub-processes relative contributions for the selected impact categories is shown in Figure 5, using the characterisation method and specifying the decommissioning step. Table 6 gives the corresponding absolute values. The most remarkable element is that the Metal cutting sub-process is found to be dominant for each decommissioning step, regardless of the impact category observed. Its contribution respectively weights 79 to 95.5% in the Dismantling step, 62.6 to 79.6% in the Clean-up step, and 96 to 99.5% in the Demolition step.

Two processes are mainly responsible for the rest of the observed impacts. The RW conditioning process, present in the Dismantling and Clean-up steps, weights 4.5 to 6.8% of the impacts for the FWAE and HT categories, 7.7 to 10.5% for the TE and AD(FF) categories, and most importantly, 20.9 and 24.1% in the GW impact category. Moreover, in the Clean-up step, the specific presence of the decontamination process induces an impact whose contribution weights from 10.8 to 28.9% depending on considered impact category, with its maximum in the HT one.

In order to understand the source of the high contribution of the Metal cutting sub-process, a breakdown of the energy and material inputs of this process will be conducted in the discussion part of this work.

5.3. Comparison of RW and conventional waste

Radioactive waste management has been identified as an important contributor to environmental impacts across the whole life cycle of an NPP (Poinssot et al. 2016). RW accounts for about 5% of all waste generated during the Fessenheim NPP decommission (EDF 2020). However, according to Figure 6 and Table 7, the impact of transport of RW is 1.8-6.6 times superior to the transport of conventional waste. Two reasons are behind this: the longer trip needed in order to dispose RW to the centralized sites and the additional weight caused by conditioning of RW.

6. Discussion

6.1. Significance of the Fessenheim case-study

With several hundred nuclear power plants in operation around the world, knowledge and feedback on the current decommissioning of nuclear power plants are important for future operations. In France alone, EDF has announced the beginning of decommissioning process for 14 nuclear reactors by 2035 (including the Fessenheim NPP). However, there are only few studies dedicated on the environmental impact of NPP decommissioning.

Under a general perspective, NPP decommissioning projects, like any other decommissioning project, share characteristics with other large construction projects like sensibility to unknowns and uncertainties about the site conditions, regulations, funding and political support, and project planning (Invernizzi et al. 2020a). Regarding environmental questions, specific features of decommissioning projects are generally an initially limited-view of: the end-state, the waste routes and storage/disposal facilities. As NPP decommissioning objective is more and more oriented towards “immediate decommissioning”, the actual processes used for electro-mechanical dismantling with radiological security, clean-up of building structure, and site rehabilitation needs to be studied thoroughly. Indeed, this would help to ensure that the management of these projects is geared towards the most environmentally appropriate solutions for given cost and duration constraints. Given the variety of nuclear programs around the world, it can be difficult to develop standardized NPP decommissioning guidelines, even if feedback-based recommendations do exist, the collection Nuclear Decommissioning Case Studies being a typical example (Laraia 2012, 2021). That said, the institutional setting of the French nuclear program allowed for a high-degree of standardization during construction (Grubler 2010). Moreover, the “end-of-life” stage of a nuclear site is oversighted by the ASN (Nuclear Safety Authority) for clean-up, and by ANDRA for RW management. Thus, a case study like the Fessenheim NPP has the potential to help decision making for several following decommissioning projects.

6.2. Impact contributions for thermal cutting

The relative contribution of each gas (oxygen, acetylene, hydrogen and argon) is displayed Figure 7. Acetylene is found to be the major contributor to the impacts of the Metal cutting sub-process, scoring between 61.1-69.3%. Adding oxygen, which represent 22.9-27.1% of the impacts in the different categories, we account for roughly 90% of the impacts of Metal cutting. Oxy-acetylene cutting has been used for metal cutting due to its affordability (Singh et al. 2021) and particularly for nuclear decommissioning thanks to the cutting speed (Gezelman 1993). The remaining contribution originates from the use of Hydrogen and Argon in Plasma cutting.

A further analysis using the Sankey network flow diagram (SIMAPRO) has been done in order to understand the origin of acetylene’s impact. The oxygen needed to produce the acetylene was found to be the biggest contributor to each LCA impact category, ranging from 61.4-69.3%. This is mainly due to the electricity consumption requirements. Theecoinvent 3.8 input process for the computation is “Electricity, medium voltage {Europe without Switzerland} | market group for | APOS, U”. For the most part, use of hard coal and lignite in the European electricity mix is the leading cause of emissions in each impact categories studied. The only exception is terrestrial ecotoxicity, where 55% of the impact is associated to the use of copper during construction of the electrical transmission network.

6.3. Thermal cutting sensitivity analysis

In this LCA, thermal cutting was selected as the sole family of techniques used for metal cutting. First reason of this choice is due to the fact that thermal cutting is cheaper and more available than mechanical cutting. Admittedly, the subject of cost in decommissioning an NPP is one of the biggest issues in a decommissioning project. The second reason is we actually had to postulate (H_a) a 100% thermal cutting proportion applied to the whole mass of metal waste, and (H_b) identical use proportions of Oxy-acetylene and Plasma cutting in Rhode 2008 and the Fessenheim NPP. These working hypotheses were necessary in the absence of elements allowing to accurately assess the expected proportion of mechanical or Plasma cutting.

As suggested by this study, thermal cutting clearly has the potential to be the biggest contributor in each impact categories studied, if used extensively for metal cutting. Therefore, a sensitivity analysis comparing environmental impacts of varying proportions of metal cutting methods allows to determine the range of results in which the real case of Fessenheim NPP decommissioning is expected to be found (within the scope of the system studied). It should be said that it is extremely improbable that Plasma cutting should replace large proportions of Oxy-acetylene cutting, due to the cost of using Plasma cutting for metal larger than 25mm (Rzeźnikiewicz 2014). Consequently, we do not analyse the variation of impacts when (H_a) is maintained and (H_b) is modified.

We thus focus on studying how the variation of (H_a) modify the predicted impacts while (H_b) is maintained. In the absence of an ecoinvent entry for mechanical cutting, we turned to the ecoinvent process “metal working” and analysed its Sankey diagram. We excluded all flows not directly related to the process of metal transformation itself: mineral extraction and initial processing, factory heating, etc. The remaining energy requirement is 17.61 MJ per kg of metal. This could then be used to define an upper bound for modelling mechanical cutting of metals in the Fessenheim NPP. French electricity mix from ecoinvent 3.8 was used as an input. Sensitivity analysis scenarios from 100% thermal 0% mechanical cutting, to 0% thermal 100% mechanical cutting were computed, with a variation of 10% defining the calculation steps.

Results of the sensitivity analysis are shown in Figure 8 and Table 8 and encompass the results for the whole system studied (“Transport” included). As we demonstrate, the more mechanical cutting is used, the less emissions are generated in the five impact categories studied. In a case of 50/50% use of the metal cutting processes, a reduction between 45-48% is predicted across all impact categories. In an unrealistic case of 100% use of mechanical cutting process (resp. 0% of thermal cutting), the predicted reduction is of at least 89-96%. This remarkable result indicates there is a huge total emission reduction potential in shifting from thermal to mechanical cutting whenever it is possible.

6.4. VLLW and over-impact of RW transport

As seen in results, the transport of RW waste has a significantly high impact compared to conventional waste. Even if RW represents only 5% of all wastes generated from the decommissioning of the NPP, their impact is about 2 to 6.6 times higher than the one of conventional waste, depending on the category. Indeed, the weight of the RW conditioning and the centralized locations of RW disposal extends the amount of trucks needed and the distance to be covered, respectively.

453 During an NPP decommissioning, the major part of the RW accounted are LLRW. In the case of the Fessenheim
1 454 NPP, it amounts to 65% in RW mass, which represents 40% of the volume to be stored. Historically, the
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3 455 implementation of a release threshold for LLRW in France have been a quickly closed but regularly reemerging
4 456 debate (Martinais 2021). The last National Radioactive Materials and Waste Management Plan (PNGMDR) to
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6 457 date acted the possibility of recycling some LLRW metals into conventional ones, firstly on the grounds of
7 458 preserving the storage capacity. If recycling is conducted in a centralized industrial site, it would probably not lead
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9 459 to a reduction of GHG associated to transport during decommissioning of the French NPP fleet, as transport from
10 460 all NPPs to this centralized recycling plant would be globally identical. A global reduction in GHG emissions
11 461 would thus need either decentralized storage or recycling plants, or alternatively a legislation change to implement
12 462 a release threshold of LLRW. The latter would allow some part of them to be treated as conventional materials, in
13 463 various industrial recycling plants closer to the different French NPPs.
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17 464 6.5. Comparison of total GWP result with literature

19 465 In this section, only GHG emissions will be considered, as both recent studies that realized an LCA about NPP
20 466 decommission (Wallbridge et al. 2013; Seier and Zimmermann 2014) focused on this metric. Firstly, we selected
21 467 the appropriate parts of their models' processes to evaluate comparable systems, as synthetized in Table 9.
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24 468 The Trawsfynydd NPP (TNPP) in Wales is a Magnox (magnesium non-oxidising) NPP whose decommissioning
25 469 process of two 235 MW reactors started in 1991. Their so-called "Plant deconstruction" and "Transport" processes
26 469 have been taking into account, which represent 54.6% of the 241,000 t CO₂ eq total GHG emission reported by
27 470 Wallbridge et al. (2013).
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31 472 The Lubmin NPP (LNPP) in Greifswald, north-eastern Germany, is a soviet conceived NPP which generated
32 473 power until 1990 and was the biggest NPP in east Germany, with five 440 MW reactors. The main difficulty here
33 473 is that, despite indicating "Transport" as a specific process inside their system boundaries, Seier and Zimmermann
34 474 actually modelled transportation as sub-processes of different superordinate processes. This makes it difficult to
35 475 accurately scale their results and compare them with our own. We thus define a lower and upper bound. The lower
36 475 bound selection includes their "Plant deconstruction" and "Cutting and decontamination" processes, while the
37 476 upper bound one also adds the "Interim storage" and "Final repository" processes. These supplementary processes
38 476 include more than just transportation, but then allow to circumscribe the validity domain of our comparison. In the
39 477 first accounting, we consider 56.4% of the 1,890,000 t CO₂ eq of total emission reported, whereas the value is
40 478 73.2% in the second accounting.
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47 482 Our study predicts that the Fessenheim NPP, composed of two 920 MW pressurized water reactor, will emits
48 483 173,040 t CO₂ eq during decommissioning (see Table 6 and 7).
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51 484 It can be observed in Figure 9 that the NPP that had the most important number of reactors (thus more buildings)
52 485 is subjected to emit more GHG during decommissioning. However, two data points only does not allow to infer
53 485 the form or even the existence of a relationship. Furthermore, according to this study, there is no obvious link
54 486 between the total installed power of the NPP and the amount of GHG emitted during decommissioning.
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57 488 Another transferability proposition, by Seier and Zimmermann (2014), was related to a possible relationship
58 488 between waste generated during decommissioning and the GHG emission of the total process. However, the
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490 authors only had the study of Wallbridge *et al.* (2013) to compare with their results. Moreover, they did not adjust
1 491 the GHG emissions value to consider the differences due to variation in system modelling, which makes their
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3 492 argument about a possible correlation rather uncertain.
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5 493 NPP decommissioning is still a unique and “exceptional” project, and doesn’t allow easy transferability, as plant
6 494 designs are usually not standardized thus requiring specific operations (Wallbridge et al. 2013; Seier and
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8 495 Zimmermann 2014). It can be also added that the previously studied NPPs started decommissioning in the early
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10 496 1990. Thus, an evolution of technical abilities and legislation has to be taken into account when comparing with
11 497 more contemporary projects. Furthermore, there is still not a sufficient amount of LCA studies regarding this
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13 498 subject, preventing any rigorous attempt to qualify results transferability. Hopefully, the expected wave of
14 499 decommissioning projects of the French NPPs in next years will make it possible to build up representative datasets
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16 500 (if LCAs are systematically carried out) which could eventually make it possible to assess the relevant factors for
17 501 data transposition.
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7. Conclusion

In this paper, we realized a life cycle assessment applied to the upcoming Fessenheim NPP decommissioning, based on limited publicly available data and transposition from scarce past studies. Accuracy of the LCIA compared to the future actual environmental impacts is always questionable by nature in this kind of exploratory research. This leads us to re-emphasize the need, as expressed in previous studies, of publicly disclosed, rich and transparent datasets coming from various projects currently running, to help the NPP decommissioning field of LCA going beyond individual case studies. If detailed dataset based on operator projections are to be available, taking into account the recent progress of the field of prospective LCA would be the next step (Arvidsson et al. 2023). In particular, implementing evolution of background processes would allow for a better assessment of this spread-over-time activity. Indeed, futurization of the ecoinvent database based on integrated assessment models results is now possible thanks to open source tools like premise (Sacchi et al. 2022). Accounting for various scenarios of shared socioeconomic pathways is expected to provide more information on the range of environmental impacts predictable. Moreover, the recent development of new methodologies for radiological health impacts in LCA could be put at use, provided the expected decommissioning radioeffluents are known (Paulillo et al. 2020, 2023). With all this taken into account, feedback of different NPP decommissions will perhaps help to find a common way to decrease the environmental impact of NPP decommissioning, without impending on cost, effectiveness and time frame of these operations. This would participate of a needed broader dynamic of studies on the end-of-life of industrial facilities, which has so far been relatively neglected, whether in the field of LCA or elsewhere (Invernizzi et al. 2020b).

By analysing the detailed impact contributions, this study emphasizes the overwhelming impact of metal cutting. For this process, unavoidable in any NPP decommissioning, we were able to quantify the tremendous importance of favouring mechanical cutting to thermal cutting every time it is possible – that is, when taking into account other typical constraints of decommissioning, such as: workers' security, project duration and cost, etc.

Finally, by comparing RW and conventional waste transport, we quantify part of the environmental cost of a country-wide centralized storage of RW, as most NPPs (like Fessenheim) are located relatively far from these storage sites. Furthermore, the majority of RW waste produced during decommissioning are VLLW. Their legal release and recycling are regularly discussed in France: the country does have a unique approach regarding this category of RW. The results of this LCA aim to inform public decision-making on the management of very low-level waste.

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622 Declaration of competing interest

623 The authors declare that they have no known competing financial interests or personal relationships that could
624 have appeared to influence the work reported in this paper.

625 Data availability

626 All data supporting the findings of this study are available within the paper, with thorough description of
627 hypotheses and calculations in the supplementary information file. Original data files will be made available on
628 request.

629 Acknowledgements

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631 French programme "Investissements d'Avenir" (ANR-11-LABX-0010) which is managed by the ANR. It also
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633 2021-2027, A1.3). The authors acknowledge Marc Allemann and Haldan Koffi for the help in the literature review.

634 Tables

635 *Table 1: Literature references selected to develop the LCI*

Type of data	Subject studied	Ref.
Electricity consumption per m ²	Energy consumption of buildings during their life cycles	(Bozdog 2007)
Quantity of conventional and radioactive waste	Fessenheim NPP decommissioning plan	(EDF 2020)
Quantity of mortar needed Mode of transport of radioactive waste	Regulations related to the classification of nuclear waste, their packaging and their transport	(ANDRA 2018)
Sanitation Metal cutting	Decommissioning of the Lubmin NPP	(Rohde 2008)
Amount of diesel needed for the concrete	Decommissioning of the Lubmin NPP	(Lünser 1998; Seier and Zimmermann 2014)
Quantity of different types of conventional waste	LCA of Modular helium reactor NPP	(Koltun et al. 2018)
Area of the Fessenheim NPP buildings	Open source map with satellite image	(OpenStreetMap)
Distance for the transfer of radioactive waste Source of energy for rail transport	Open source map of railways	(OpenRailwayMap)

636 *Table 2: Inputs during the Dismantling process*

Inputs	Amount	Unit	Sub-process
Oxygen	34,425.1	m ³	Electromechanical (metal cutting)
Acetylene	18,118.5	m ³	
Hydrogen	3,623.7	m ³	
Argon	3,623.7	m ³	
Cement mortar for FAMA VC	24,463.3	t	Radioactive Waste conditioning
Diesel (energy)	6,699.8	L	Deconstruction (concrete)

637 *Table 3: Inputs during the Clean-up process*

Inputs	Amount	Unit	Sub-process
Oxygen	2,979.1	m ³	Metal cutting
Acetylene	1,567.9	m ³	
Hydrogen	313.6	m ³	
Argon	313.6	m ³	
Water	1,730	m ³	Decontamination
Steel Gravel	61.4	t	
Phosphoric acid	30	m ³	
Oxalic acid	16.6	t	
Cement mortar for FAMA VC	3,094.7	t	Radioactive Waste conditioning

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Table 4: Inputs during the Demolition process

Input	Amount	Unit	Sub-process
Electricity	981,375.6	kWh	Deconstruction (general)
Diesel (energy)	1,402,935	L	
Oxygen	284,657.6	m ³	Metal cutting
Acetylene	149,819.8	m ³	
Hydrogen	29,964	m ³	
Argon	29,964	m ³	

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Table 5: Inputs during the Transport process

Input	Amount	Unit	Sub-process
Road	16,170,000	tkm	Conventional waste
Road	14,619,541	tkm	Radioactive waste
Electric train	73,800,000	tkm	
Diesel train	5,200,000	tkm	

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Table 6: LCIA values of each elementary process according to impact categories studied.

Impact category		Abiotic depletion (fossil fuels)	Global warming (GWP100a)	Human toxicity	Fresh water aquatic ecotox.	Terrestrial ecotoxicity
Unit		MJ	kg CO ₂ eq	kg 1.4-DB eq	kg 1.4-DB eq	kg 1.4-DB eq
Dismantling	Deconstruction (concrete)	317,161	23,101	2,812	2,376	7
	Electromechanical (Metal cutting)	209,887,190	17,519,757	11,339,419	13,441,155	57,868
	RW conditioning	20,202,890	4,645,045	82,839	631,434	4,823
	Total (Dismantling)	230,407,241	22,187,903	12,170,621	14,074,965	62,698
Clean-up	Decontamination	3,427,691	323,436	442,238	34,589	677
	Metal cutting	18,198,328	1,518,493	982,291	1,163,627	501
	RW conditioning	2,542,643	584,604	104,257	79,469	607
	Total (Clean-up)	24,168,661	2,426,534	1,528,787	1,588,987	6,295
Demolition	Deconstruction (general)	67,333,760	4,909,874	67,544	565,208	2,471
	Metal cutting	1,623,307,200	135,449,660	87,620,295	103,795,380	44,698
	Total (Demolition)	1,690,641,000	140,359,540	88,295,735	104,360,590	449,452
All	Total	1,945,216,902	164,973,977	101,995,143	120,024,542	518,445

Table 7: Absolute values of environmental impacts for Transport

Environmental Impact	Unit	Conventional Waste	Radioactive Waste	Total
Abiotic depletion (fossil fuels)	MJ	39,022,382	70,243,258	109,265,640
Global warming (GWP100a)	kg CO ₂ eq	2,615,667	5,450,198	8,065,865
Human toxicity	kg 1.4-DB eq	1,018,414	2,955,977	3,974,391
Fresh water aquatic ecotox.	kg 1.4-DB eq	411,183	2,713,010	3,124,193
Terrestrial ecotoxicity	kg 1.4-DB eq	3,342	8,818	12,161

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Table 8: LCIA Results relative to the use of thermal and mechanical cutting

Ratio of thermal cutting		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
Abiotic depletion (fossil fuels)	MJ	2.06E+09	1.87E+09	1.68E+09	1.50E+09	1.31E+09	1.13E+09	9.45E+08	7.59E+08	5.74E+08	3.89E+08	2.04E+08
Global warming (GWP100a)	kg CO2 eq	1.73E+08	1.58E+08	1.42E+08	1.27E+08	1.11E+08	9.60E+07	8.05E+07	6.51E+07	4.96E+07	3.42E+07	1.87E+07
Human toxicity	kg 1.4-DB eq	1.06E+08	9.60E+07	8.60E+07	7.60E+07	6.60E+07	5.60E+07	4.61E+07	3.61E+07	2.61E+07	1.61E+07	6.10E+06
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.23E+08	1.11E+08	9.95E+07	8.77E+07	7.58E+07	6.40E+07	5.21E+07	4.03E+07	2.85E+07	1.66E+07	4.80E+06
Terrestrial ecotoxicity	kg 1.4-DB eq	5.31E+05	4.80E+05	4.29E+05	3.78E+05	3.27E+05	2.76E+05	2.25E+05	1.74E+05	1.23E+05	7.22E+04	2.13E+04

Table 9: Scaling to make previous publications of interest comparable to our modelling of the Fessenheim NPP

Publication	GW reported value (t CO2 eq)	Processes selected for scaling	Process contribution (%)	Total (%)	GW scaled value (t CO2 eq)
Wallbridge et al. (2013)	241,000	Plant deconstruction	51.5	54.6	132,000
		Transport	3.1		
Seier & Zimmerman (2014)	1,890,000	Plant deconstruction	48.7	56.4 – 73.2	1,070,000 – 1,380,000
		Cutting & decontamination	7.6		
		Interim storage and Final repository (LLW)	16.8		

Figure caption

- 1 650
- 2 651 Figure 1: Presentation of the Fessenheim NPP. (a) General location (b) Overview of the plant (c) Main
- 3 functional buildings (OpenStreetMap).
- 4 652
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- 6 653 Figure 2: System Boundary for the LCA of Fessenheim NPP decommissioning
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- 8 654 Figure 3: Map of French NPP and decommission RW storage site
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- 10 655 Figure 4: Relative contribution of elementary process depending to CML IA midpoint impacts
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- 12 656 Figure 5: Contribution analysis of each elementary process according to impact categories studies
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- 14 657 Figure 6: Relative contribution of the transport processes to LCIA results
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- 16 658 Figure 7: Relative contribution of Metal cutting sub-processes to LCIA results
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- 18 659 Figure 8: Decrease of impacts when replacing thermal by mechanical cutting
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- 20 660 Figure 9: Comparison of GHG emission of different NPP decommission LCIA after adjustments for systems
- 21 comparability (Wallbridge et al. 2013; Seier and Zimmermann 2014)
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662 Figures

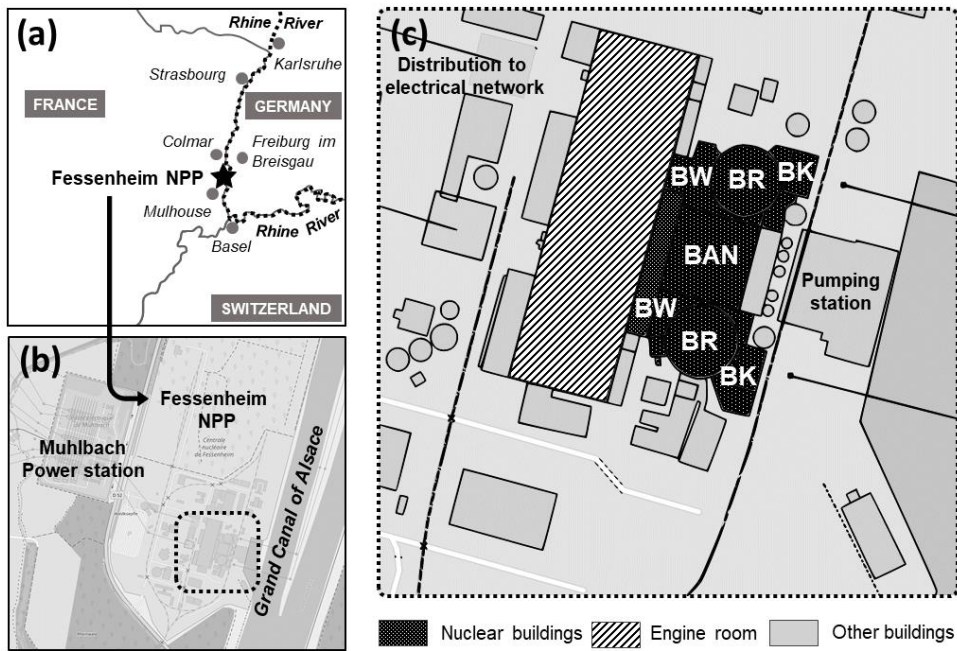


Figure 1: Presentation of the Fessenheim NPP.

(a) General location (b) Overview of the plant (c) Main functional buildings (OpenStreetMap).

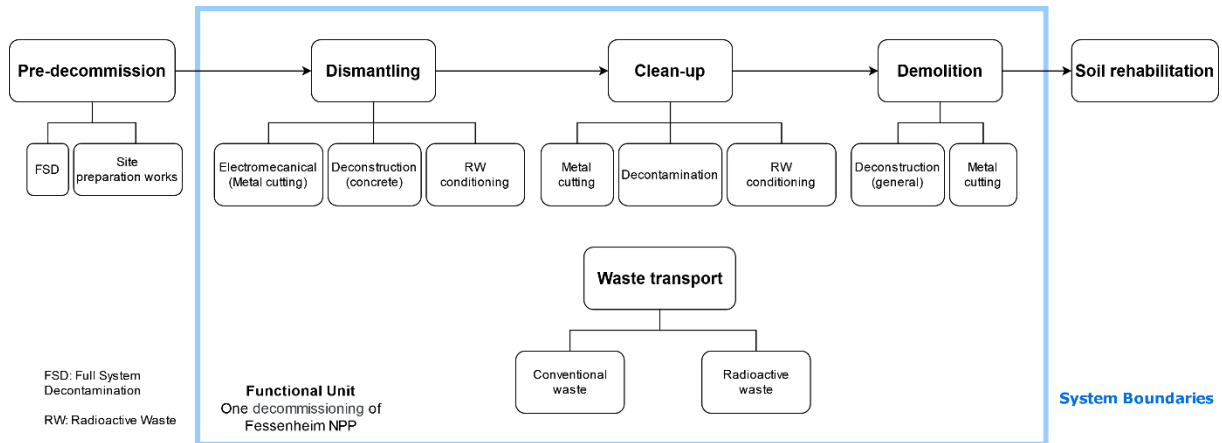


Figure 2: System Boundary for the LCA of Fessenheim NPP decommissioning

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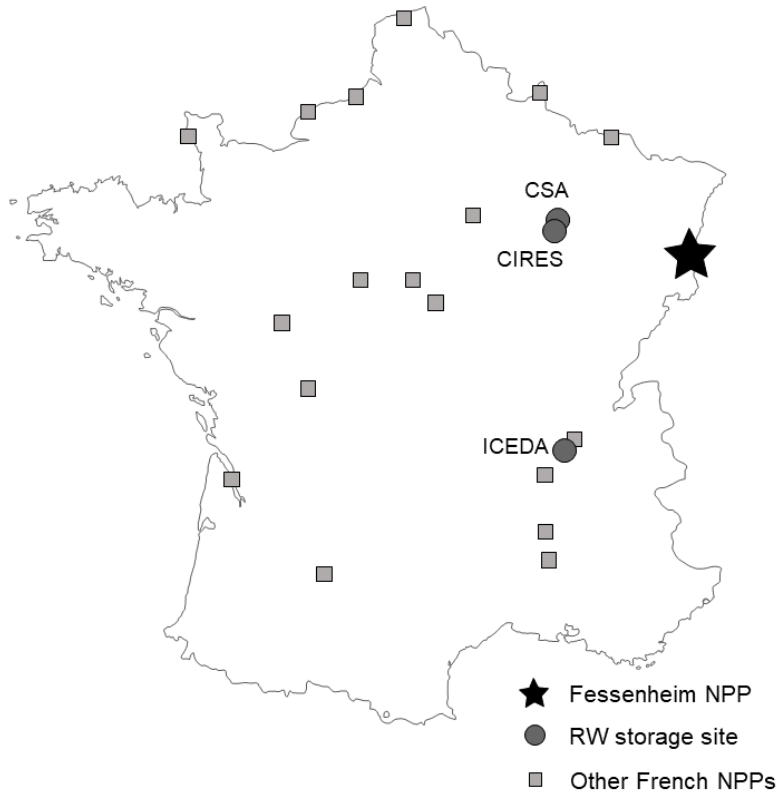


Figure 3: Map of French NPP and decommission RW storage site

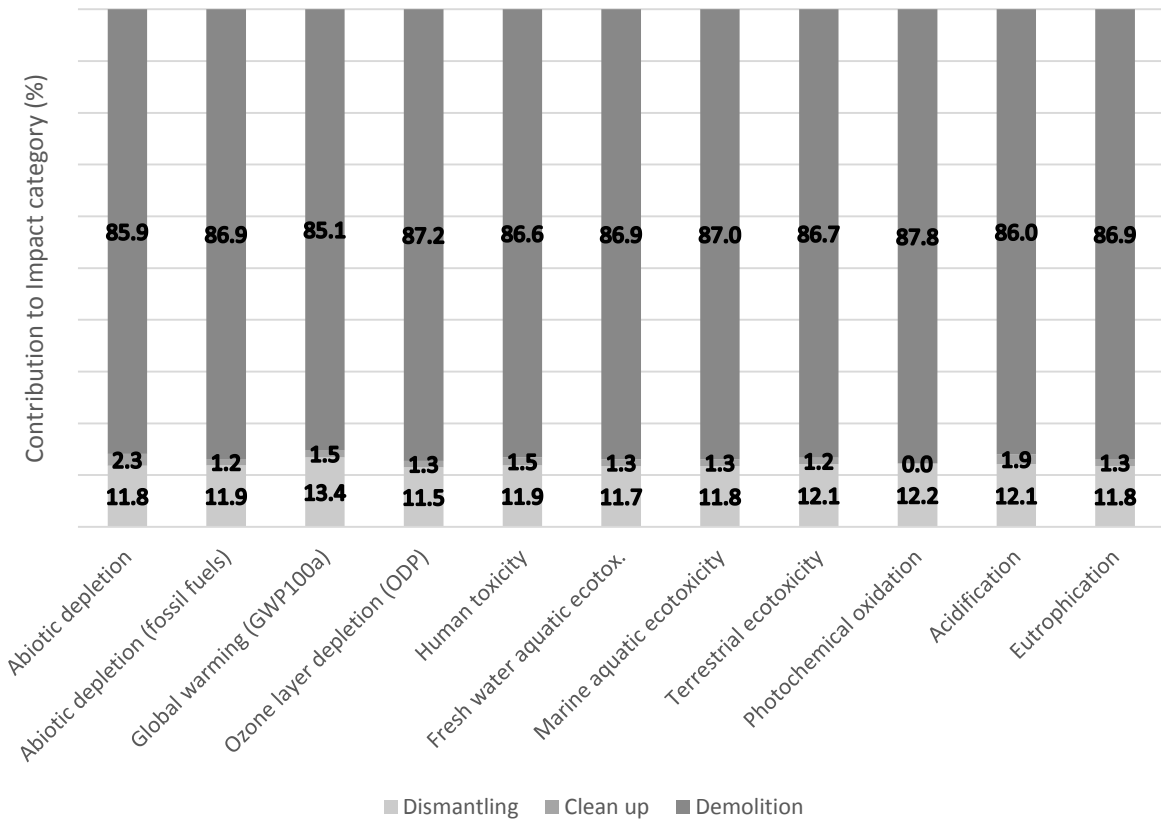


Figure 4: Relative contribution of elementary process depending to CML IA midpoint impacts

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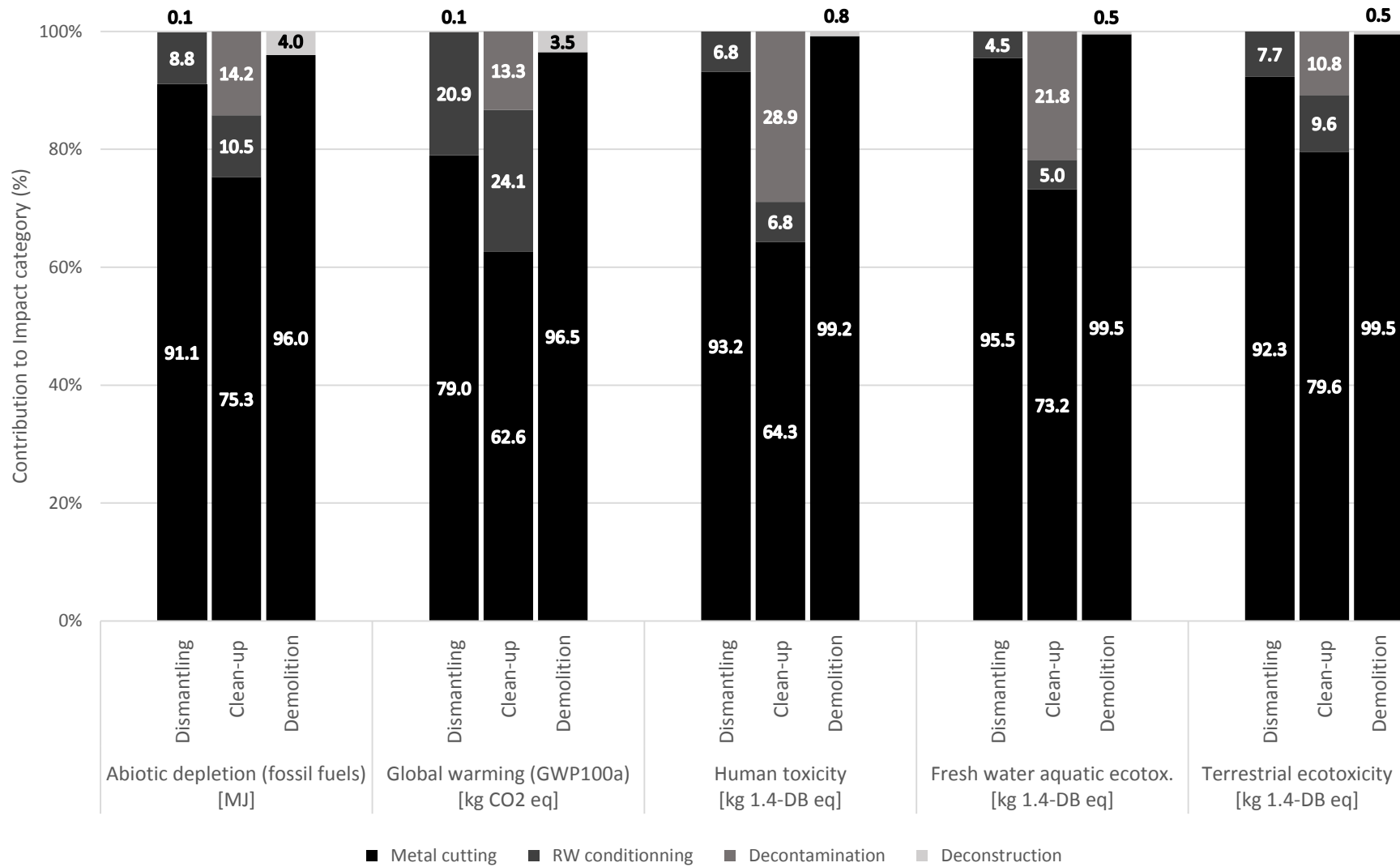


Figure 5: Contribution analysis of each elementary process according to impact categories studies

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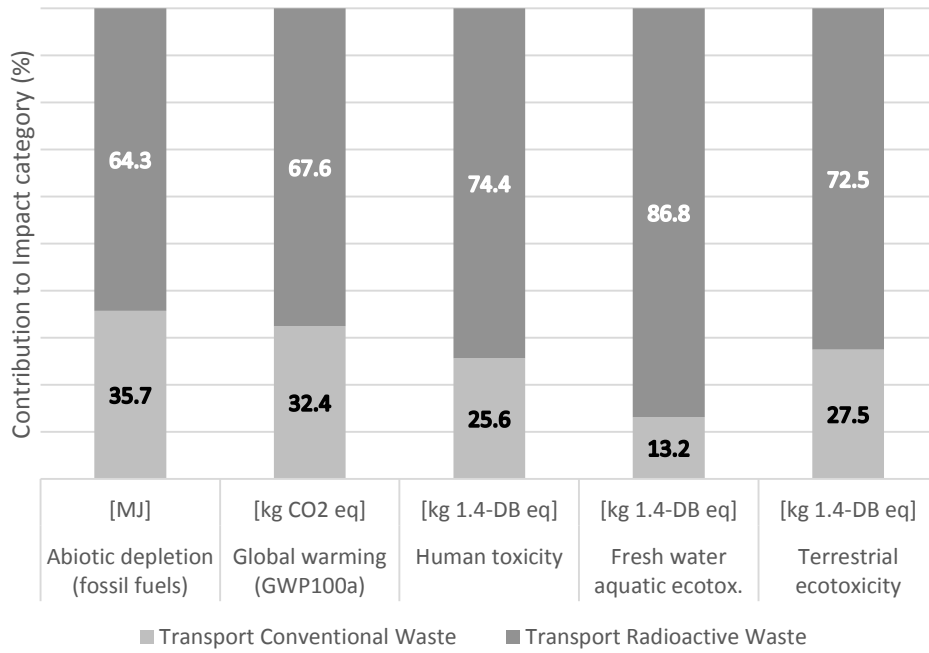


Figure 6: Relative contribution of the transport processes to LCIA results

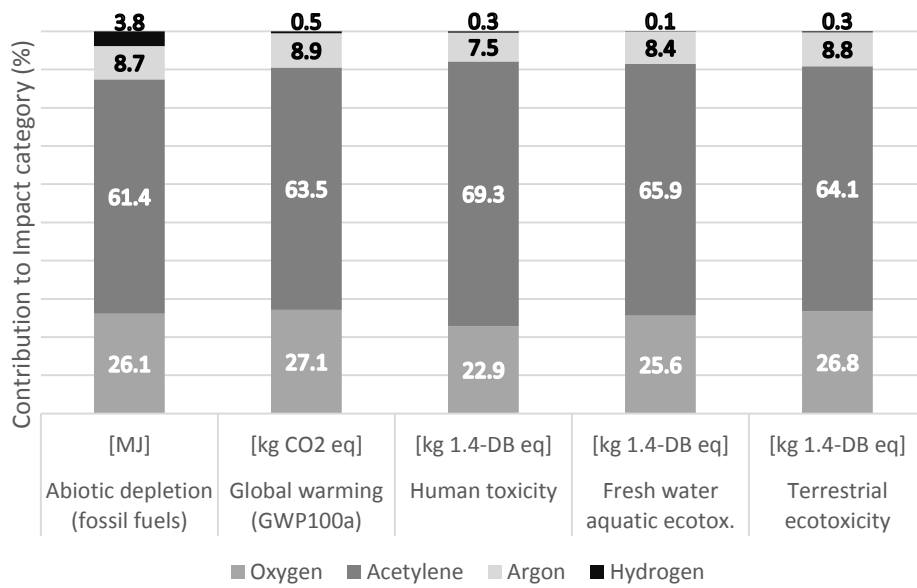


Figure 7: Relative contribution of Metal cutting sub-processes to LCIA results

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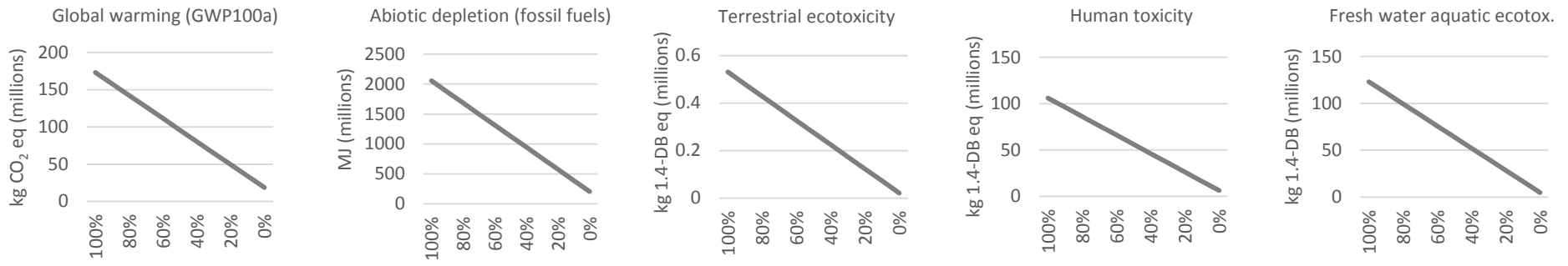


Figure 8: Decrease of impacts when replacing thermal by mechanical cutting

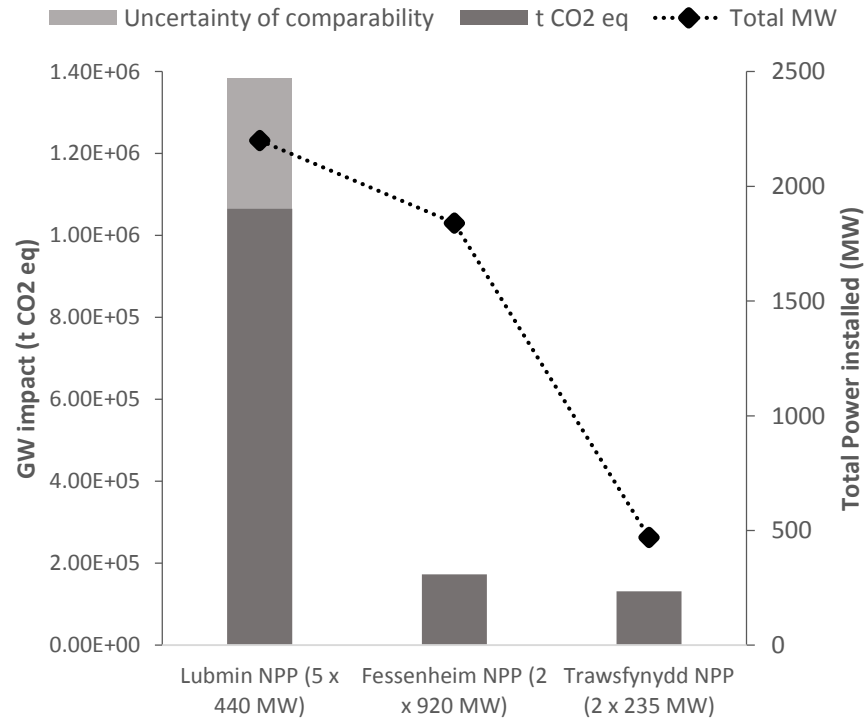


Figure 9: Comparison of GHG emission of different NPP decommission LCIA after adjustments for systems comparability (Wallbridge et al. 2013; Seier and Zimmermann 2014)

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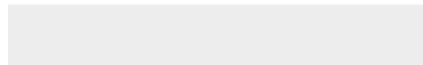
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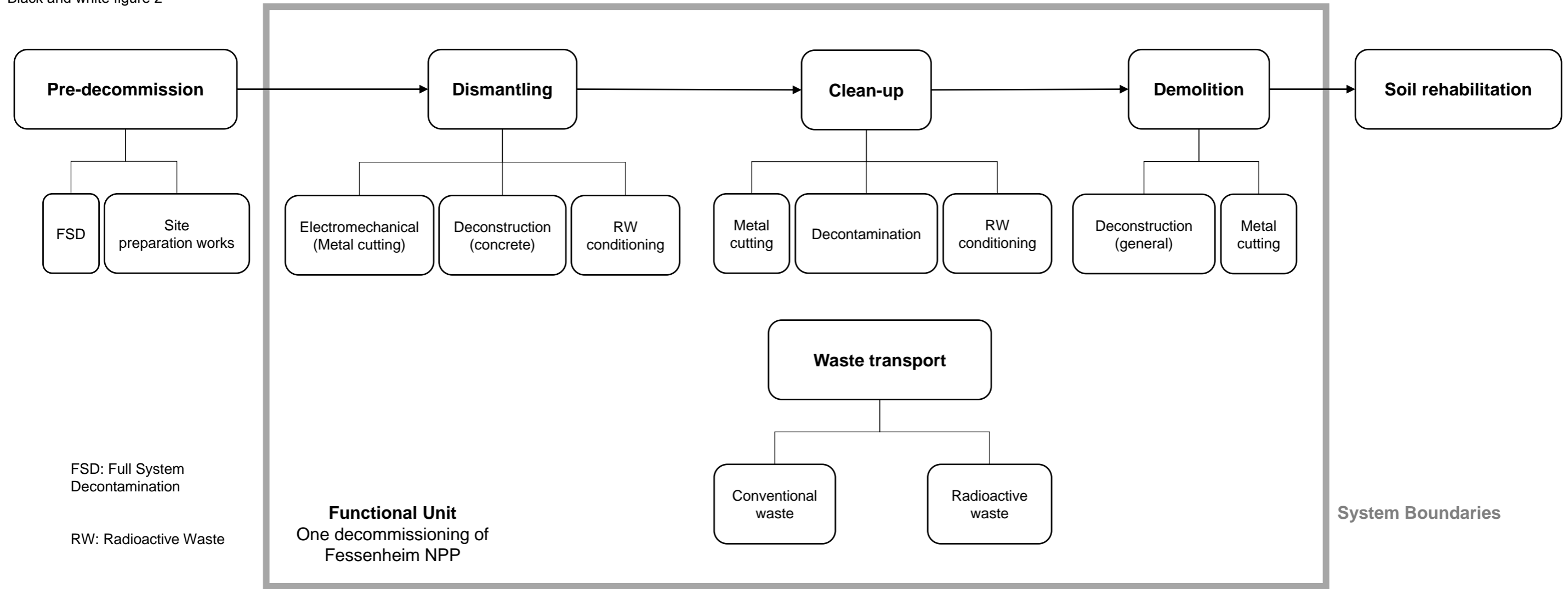
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Supplementary Material

SI NPP Decom LCA reviewed JLCA-D-23-00380.docx



Black and white figure 2



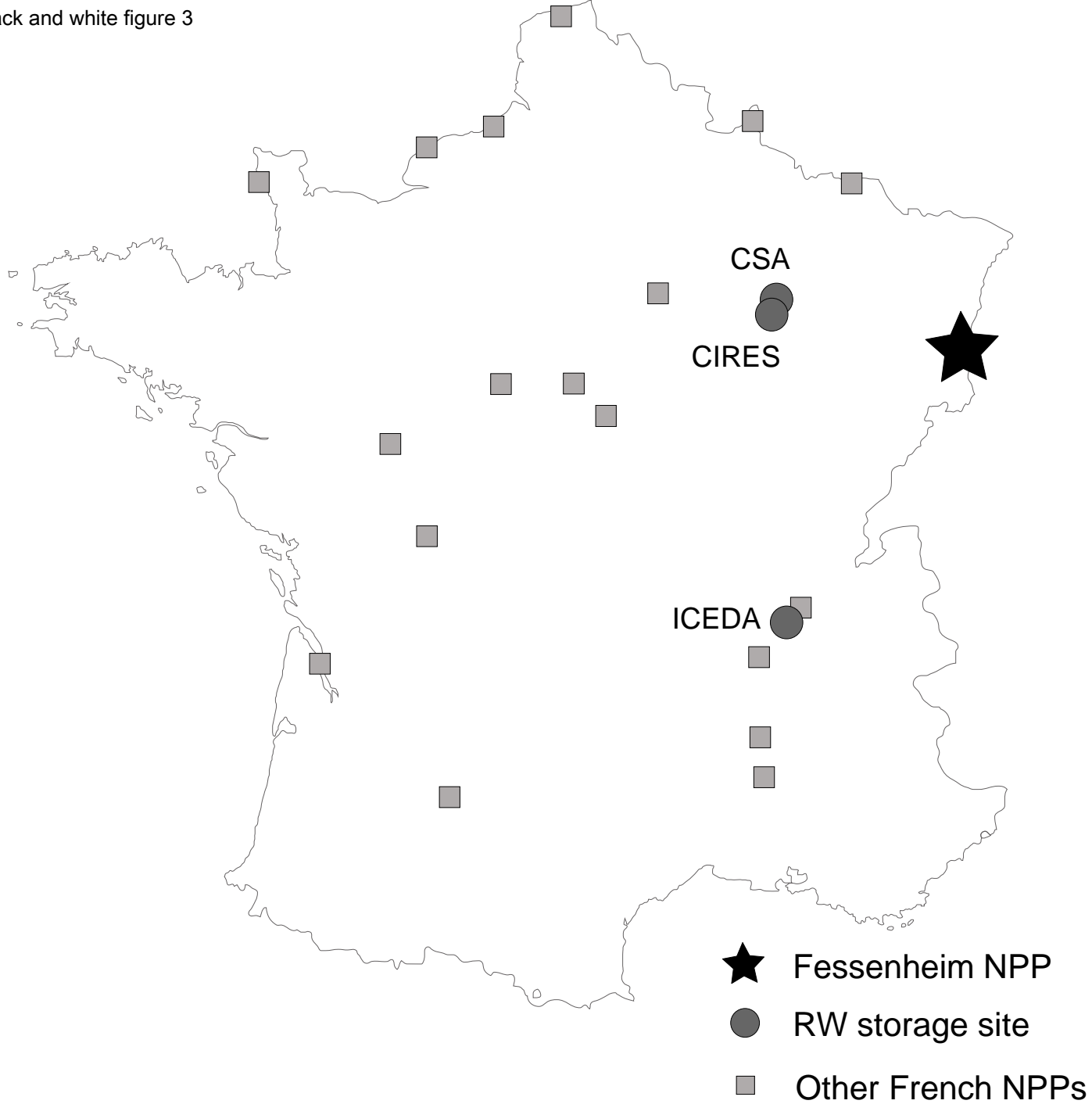
FSD: Full System
Decontamination

RW: Radioactive Waste

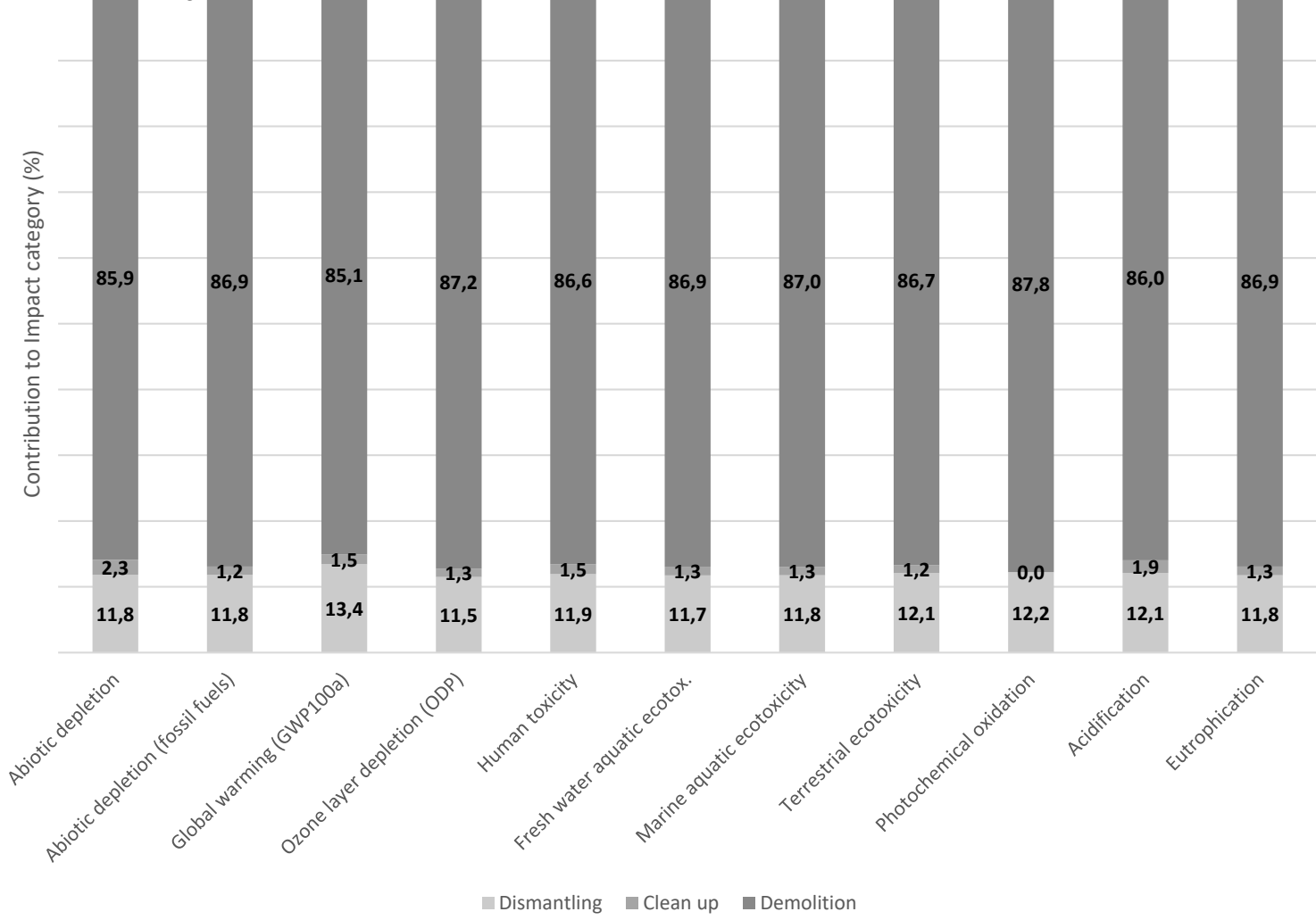
Functional Unit
One decommissioning of
Fessenheim NPP

System Boundaries

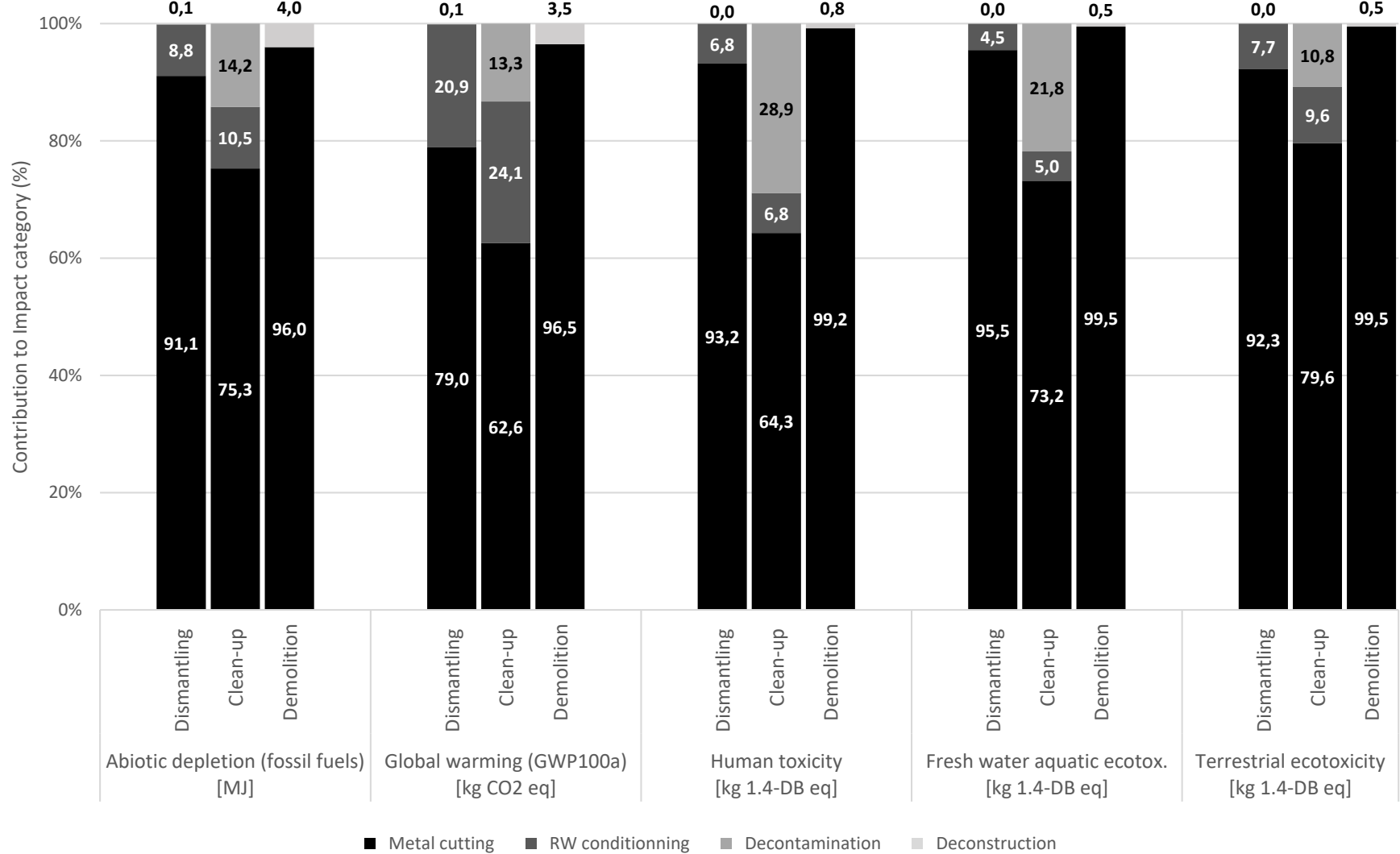
Black and white figure 3



Black and white figure 4

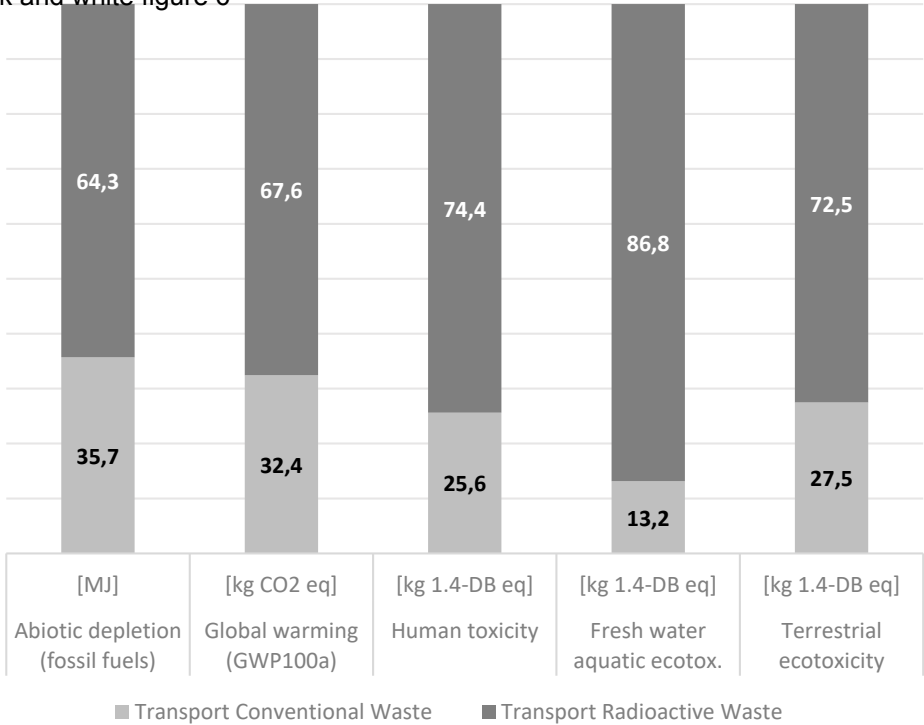


Black and white figure 5



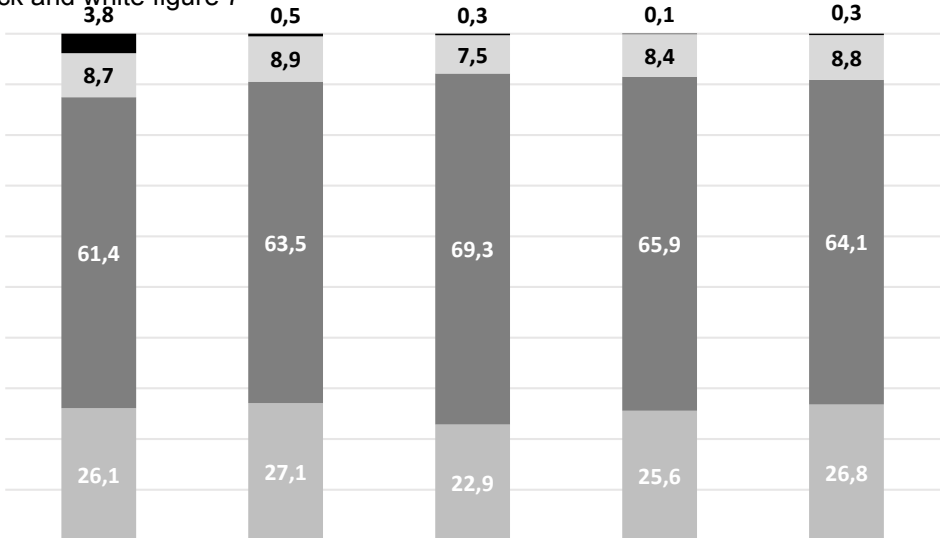
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Contribution to Impact category (%)



Black and white figure 7

Contribution to Impact category (%)

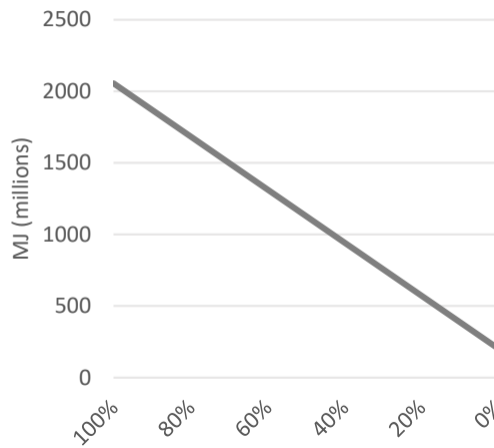


[MJ]	[kg CO2 eq]	[kg 1.4-DB eq]	[kg 1.4-DB eq]	[kg 1.4-DB eq]
Abiotic depletion (fossil fuels)	Global warming (GWP100a)	Human toxicity	Fresh water aquatic ecotox.	Terrestrial ecotoxicity

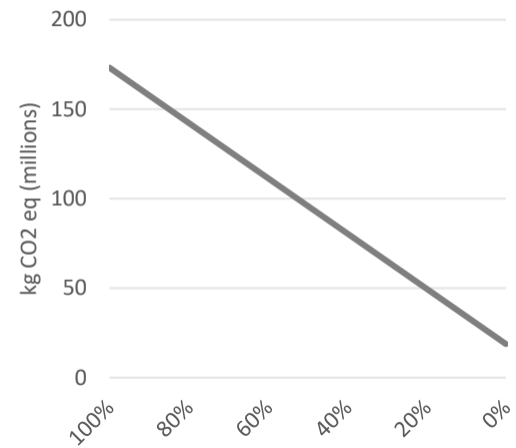
Oxygen
 Acetylene
 Argon
 Hydrogen

Black and white figure 8

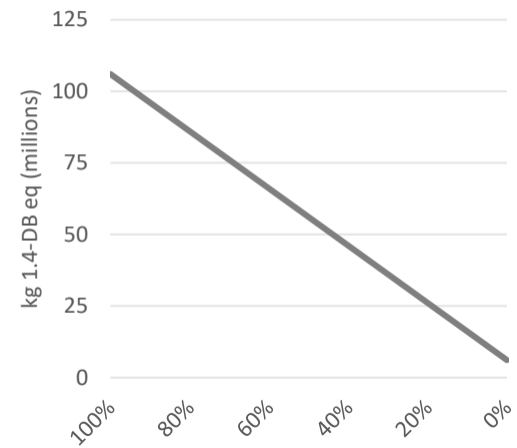
Abiotic depletion (fossil fuels)



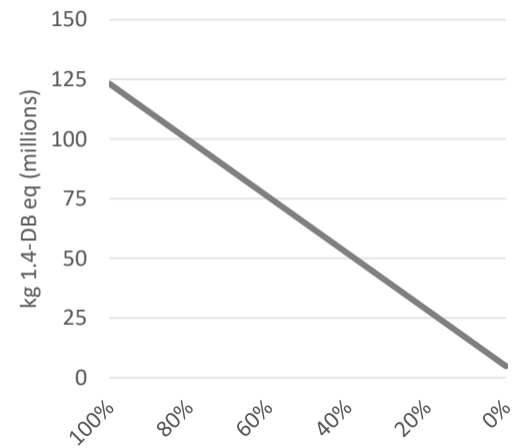
Global warming (GWP100a)



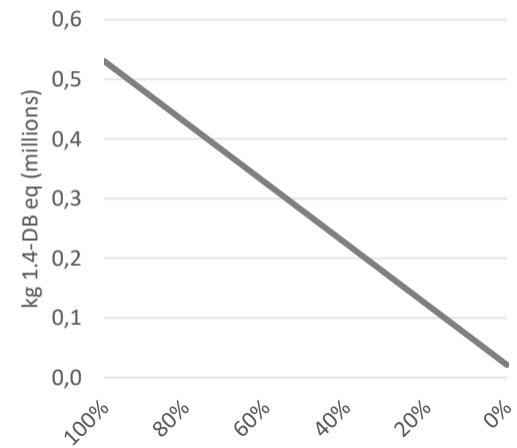
Human toxicity



Freshwater aquatic ecotox.

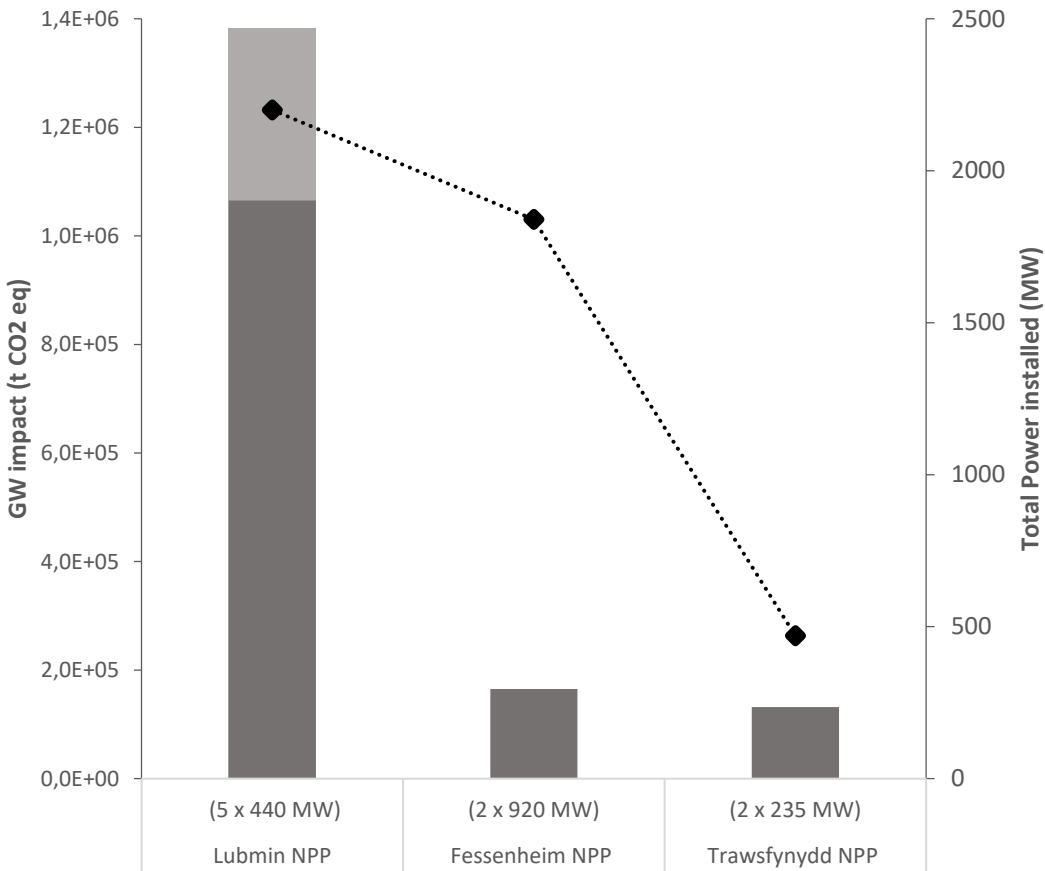


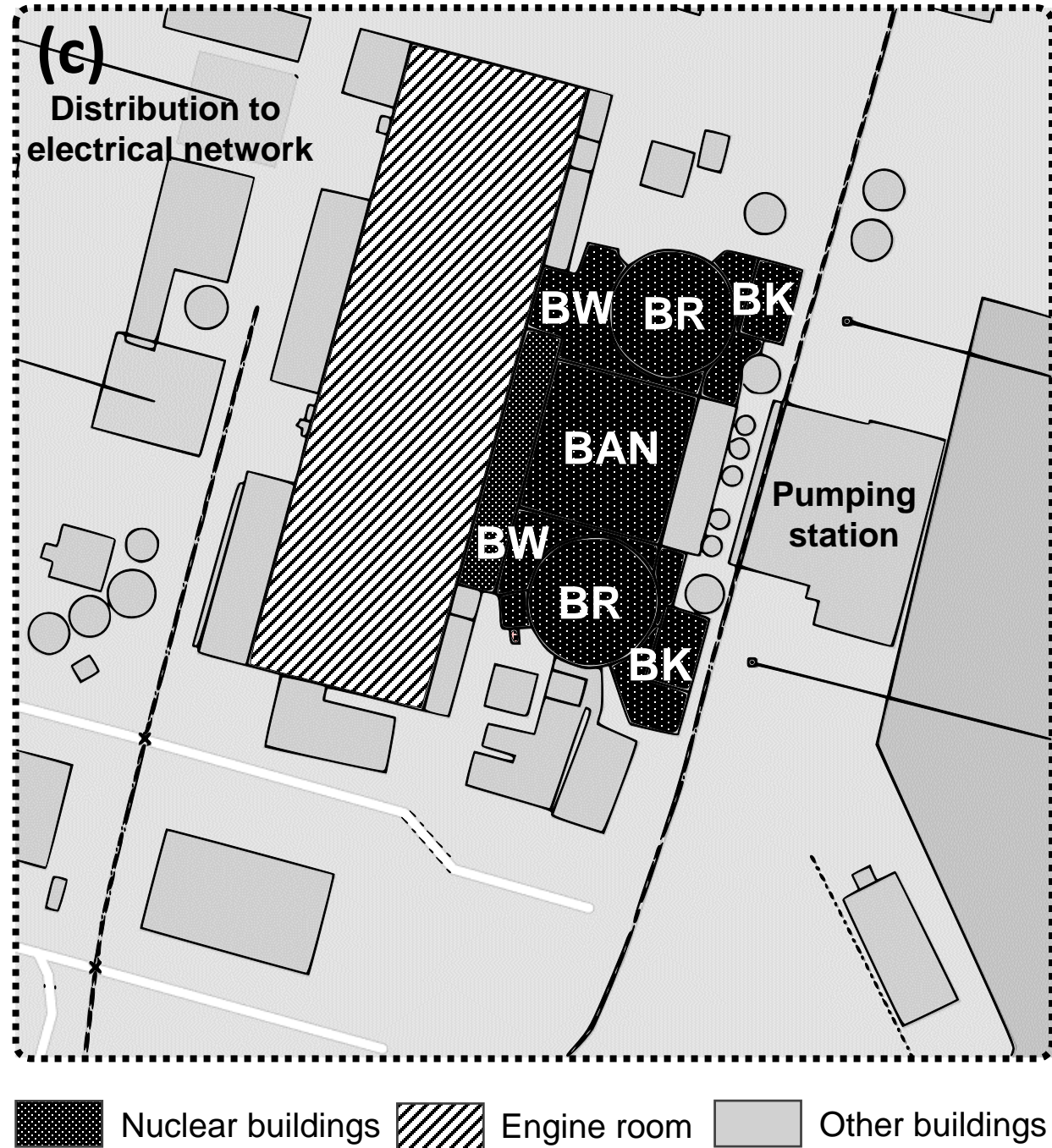
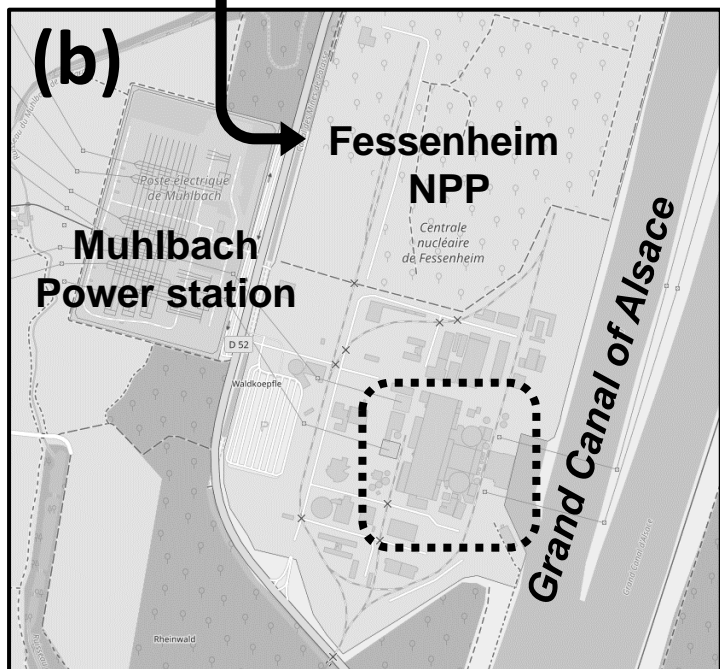
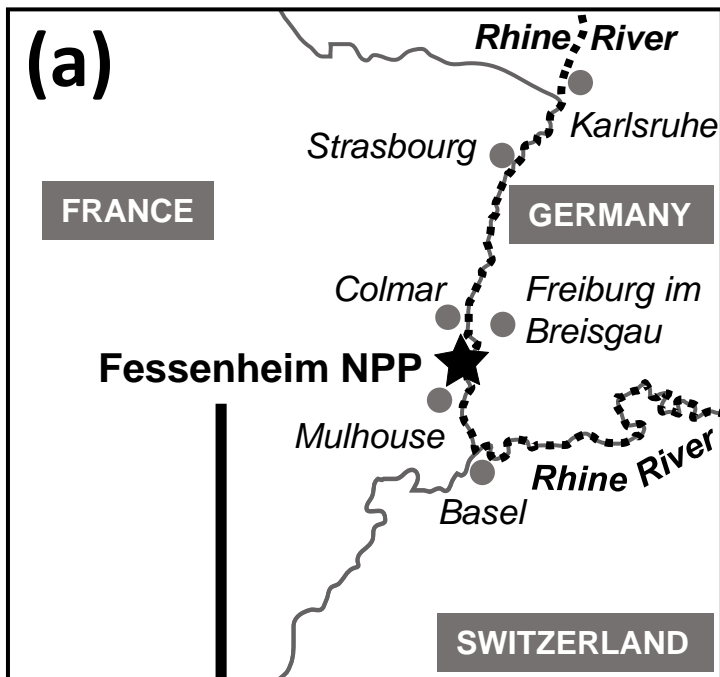
Terrestrial ecotoxicity



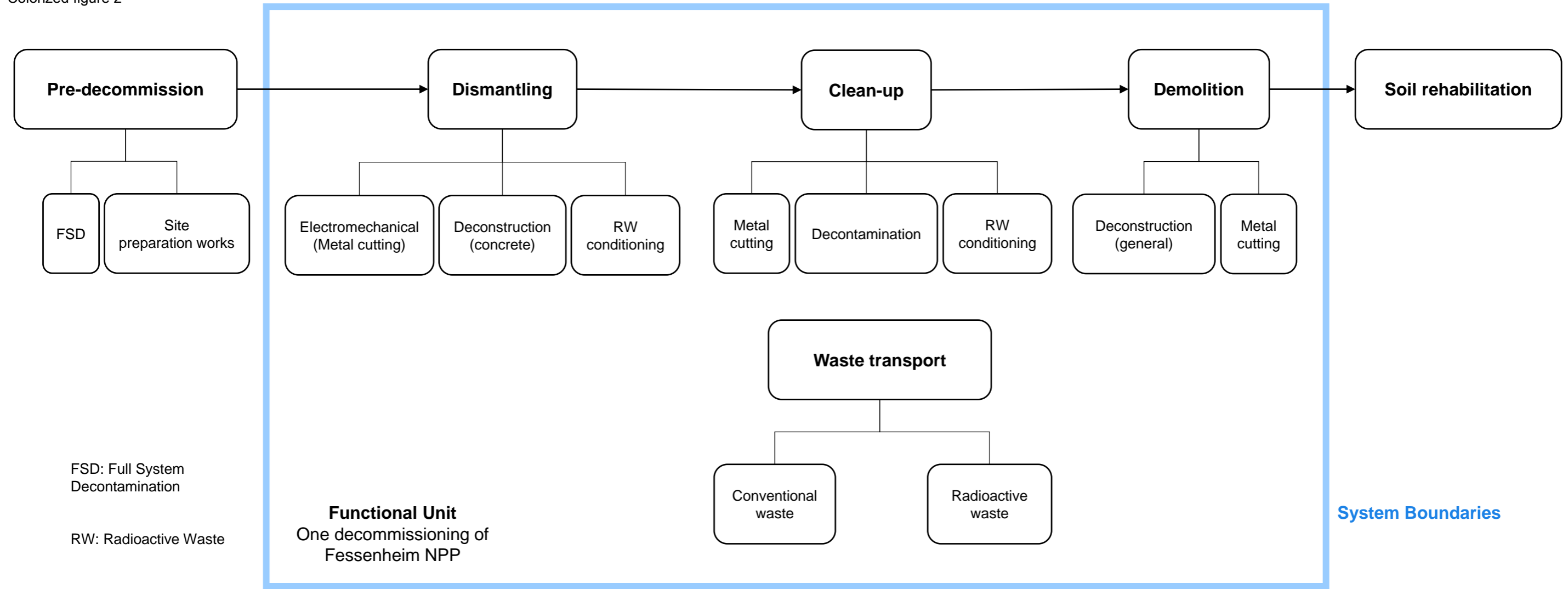
Black and white figure 9

Uncertainty of comparability t CO2 eq Total MW

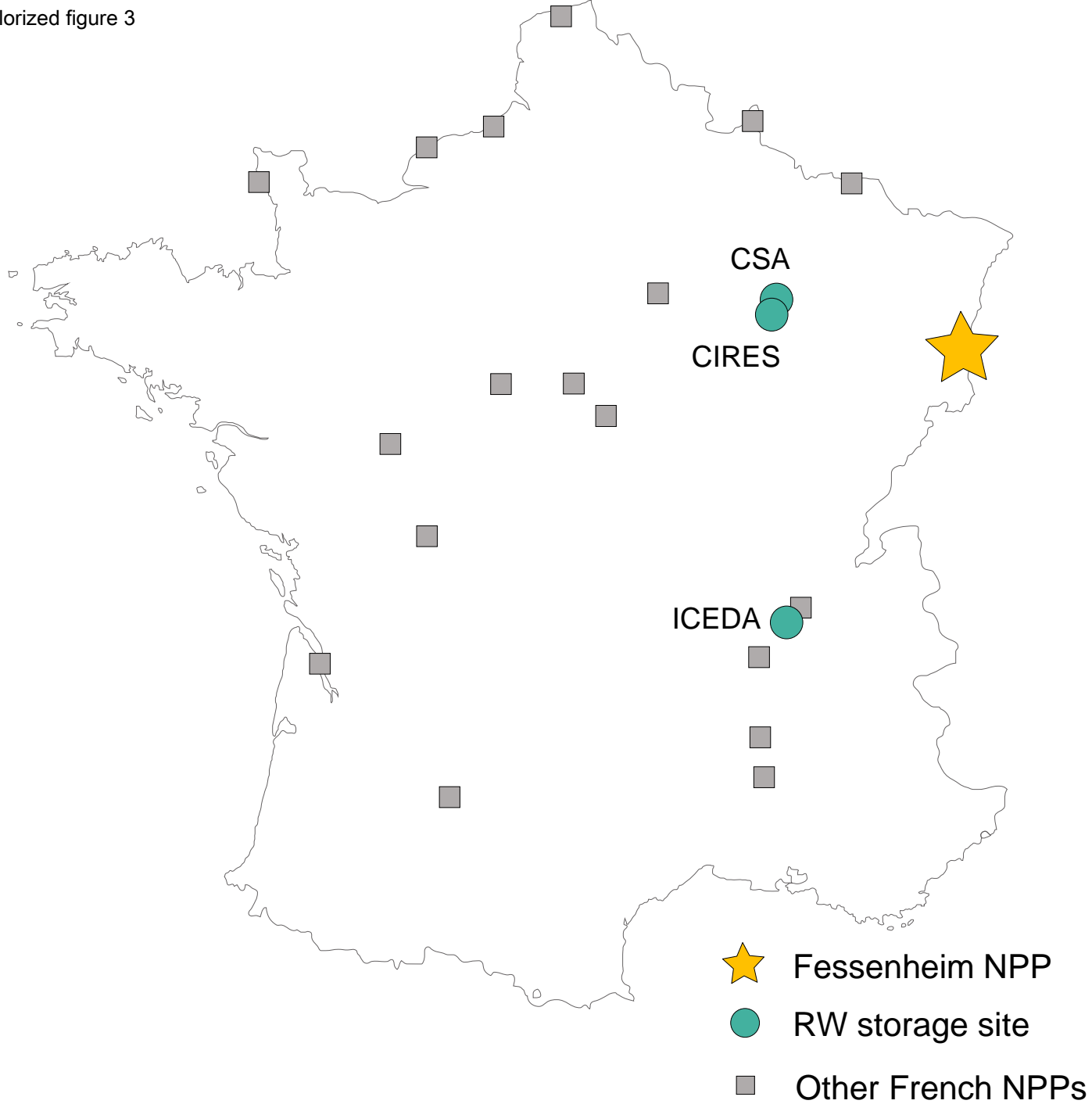




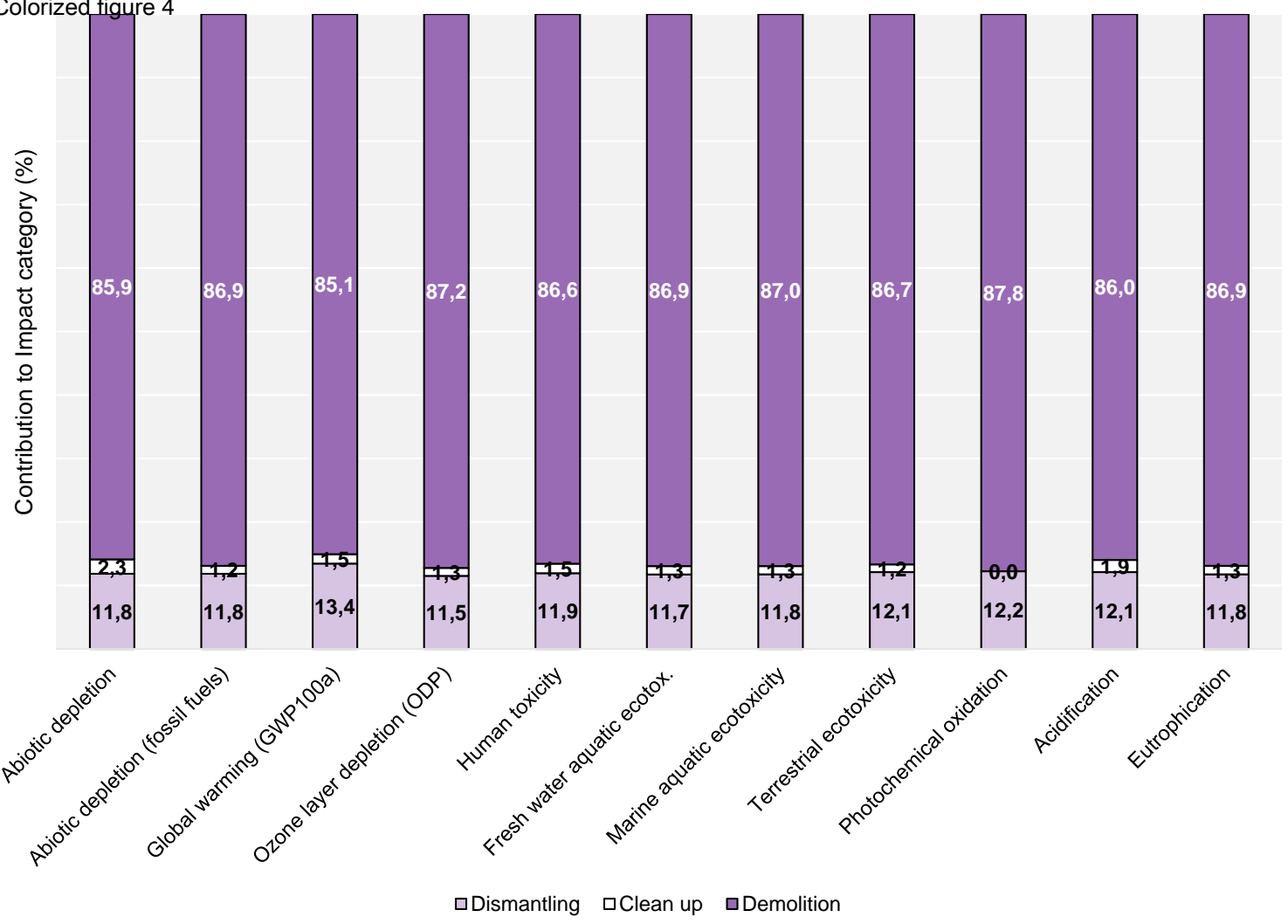
Colorized figure 2



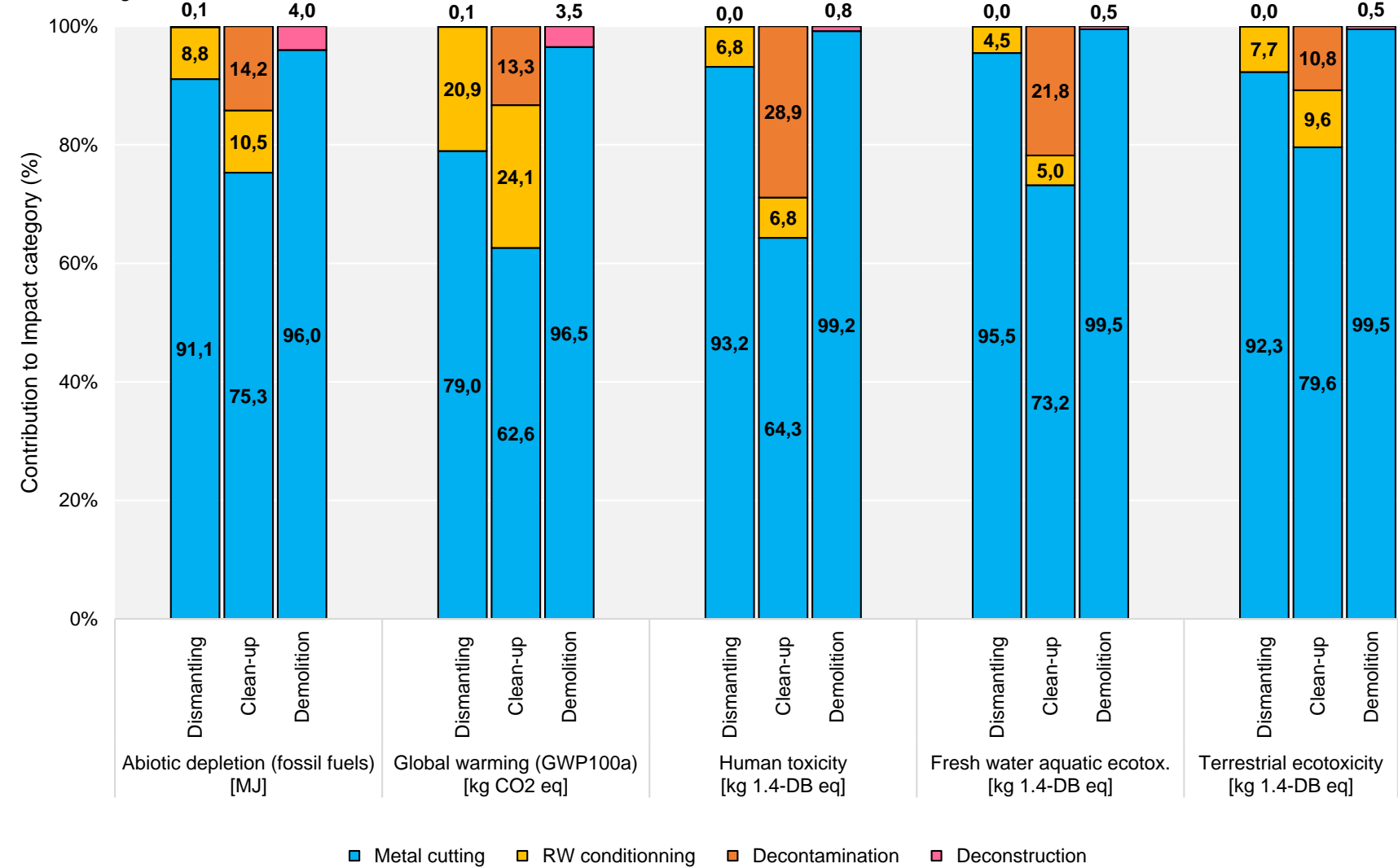
Colorized figure 3



Colorized figure 4

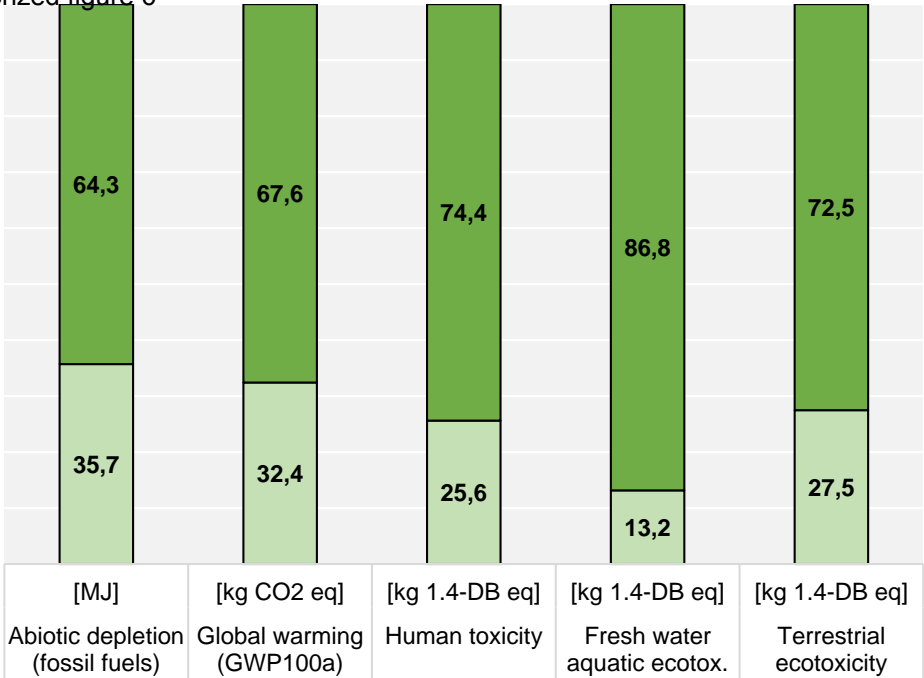


Colorized figure 5



Colorized figure 6

Contribution to Impact category (%)

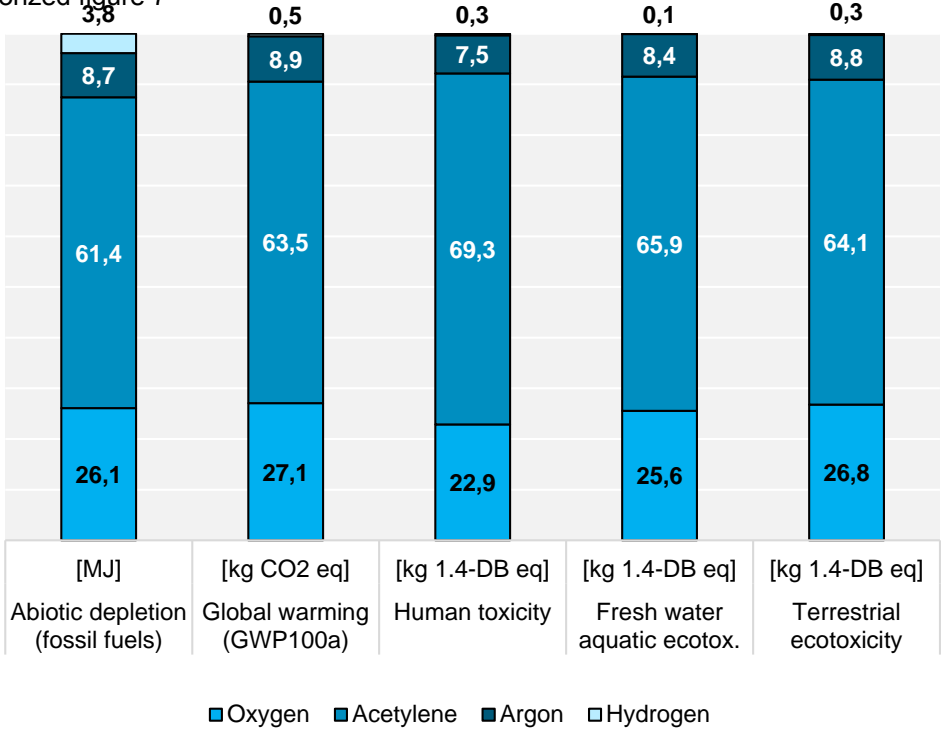


□ Transport Conventional Waste

■ Transport Radioactive Waste

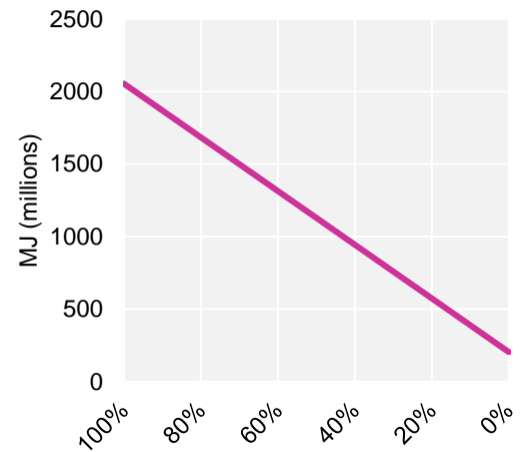
Colorized figure 7

Contribution to Impact category (%)

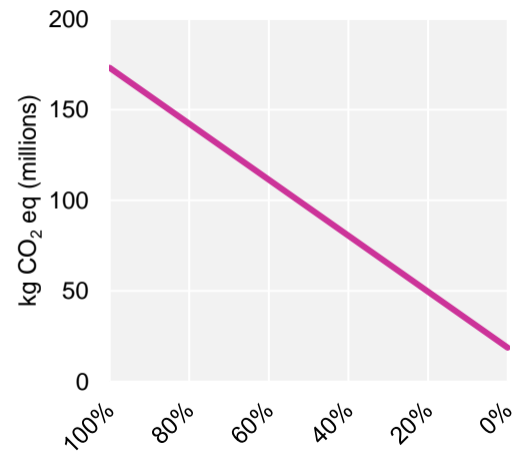


Colorized figure 8

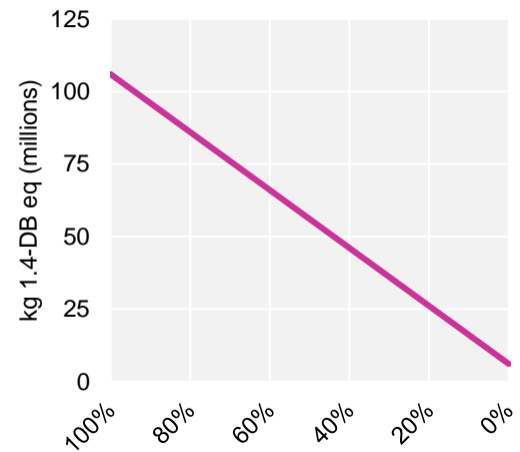
Abiotic depletion (fossil fuels)



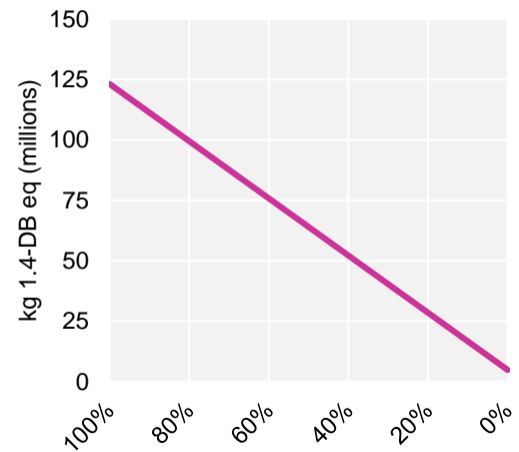
Global warming (GWP100a)



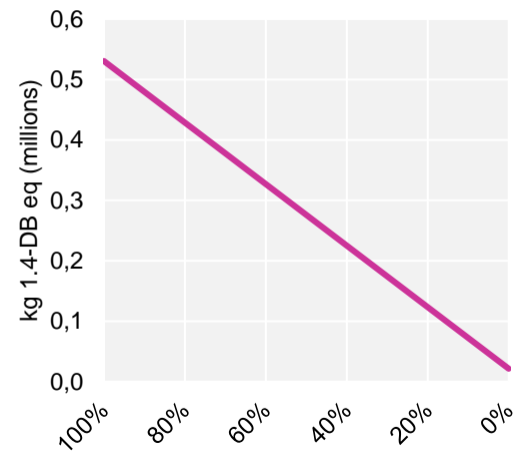
Human toxicity



Freshwater aquatic ecotox.



Terrestrial ecotoxicity



Colorized figure 9

