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Nuclear waste repository as a scenario problem

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Nuclear waste repository as a scenario problem: Developing epistemic understanding

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Summary

The goal of this report is to increase understanding of the nuclear waste repository as an application case for the scenario method. The project was part of the Finnish research programme on nuclear waste management (KYT2022). The project goals were: (1) to "contribute to the advancement of overall safety by distilling "lessons learned" from several application domains on the uses of scenario analysis in the identification and analysis of uncertainty factors", and (2) to "formulate systematic frameworks and structured approaches which can be deployed to assess the overall safety of nuclear waste repositories".

The report is organised as follows:

- Chapter 2 gives the necessary background information on a nuclear waste repository system and the context of scenarios in decision-making in connection with nuclear waste management.
- Chapter 3 shows the results of an extensive literature review of scenario approaches. The data consisted of almost 400 articles published in academic journals in four fields (Energy studies, Environmental studies, Risk & Safety analysis, and Foresight). We identified four main scenario approaches that represent different epistemic traditions characterised by different goals of knowledge production and methodological approaches. In order to create an integrative view on scenario approaches, we developed an *epistemic scenario framework*, which is a 2x2 matrix that differentes scenario purposes (normative/explorative) and scenario contents (focus on the system / external environment).
- In Chapter 4, we apply the developed epistemic approach in the analysis of nuclear waste repository scenarios, and we analyse the special characteristics of the nuclear waste repository system and requirements for the scenario analysis as part of the overall safety assessment of the repository systems.
- Chapter 5 presents our findings and shows how the epistemic scenario framework can be useful in the analysis of scenario problems and evaluating the needs for a proper scenario approach in the context of nuclear waste management.

Our analysis of the nuclear waste repository scenarios concludes that the task requires systematic approaches that involve normative and explorative elements. In the literature review, we found similar epistemic features in relation to approaches called *scenario analysis* and *safety analysis*. These approaches combine scenarios and model-based impact assessment. They utilise systematic, mathematical methods in scenario development, but brainstorming or other types of idea generation or workshop approaches may be essential for improving the explorative aspect of the analysis. A nuclear waste repository creates a challenging task for scenario analysis due to its safety-critical character and the long time frame required for the analysis, as well as the multidisciplinary character of phenomena present in the system. Therefore, methodological development is possible only in processes that closely integrate methodological approaches with the application context. This study increased the preparedness for an integrative approach from a theoretical perspective. But for complete integration of theory and practice, a different research design (such as in action research) would be needed.

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Contents

1 Introduction

This project is part of the Finnish research programme on nuclear waste management (KYT2022). Therefore, our main attention focuses on the safety of the nuclear waste repository system. However, we take a very specific view on this topic and concentrate on the scenario method. We describe issues relating to nuclear waste management only to the extent required for understanding the challenges of scenario-making in this context. The aim of this report is to increase understanding of nuclear waste management as a “scenario problem”, by which we mean understanding why scenarios are needed in the context of nuclear waste management, for what purpose they are used, and how this affects the content of scenarios. In other words, we approach the use of scenarios from an epistemic perspective. This means that we are interested in scenarios as knowledge about the future, and we approach scenario development as a process of knowledge creation.

Scenarios are widely used in different contexts and for different purposes, ranging from strategic management (Codet, 2000; Bowman, 2016) to environmental studies (Tourki et al., 2013; Wilkinson et al., 2013) and energy studies (Nielsen & Karlsson, 2017), from foresight and public policy (Volkery & Ribeiro, 2009; Wright et al., 2020) to operations studies and multi-criteria decision analysis (Durbach & Steward, 2012). This profusion of use contexts is connected with a variety of methodological approaches in scenario development and makes it a challenging task to seize the entire field of scenarios or select a proper methodological approach for a certain purpose. The scholarly community has tried to take on this task, and the result has been a large number of reviews and typologies that present different categorisations and frameworks to understand the field. We use this literature in our study as a source, but we claim that previous attempts have largely disregarded the epistemic aspect of scenario studies, even if it is an essential starting point for truly integrative approaches to understand the similarities and differences between different scenario approaches.

To illustrate how earlier categorisations failed to find integrative structures, we provide two examples. Tietje (2005) divides scenario analyses from the mathematical perspective into three different types: holistic, model, and formative scenario analysis. The emphasis on the formal methodological approach in scenario development increases from the first to the last one. Holistic scenarios refer to approaches that utilise disciplinary expertise and intuitive interpretation of various qualitative and quantitative data (e.g. trend extrapolation) in scenario creation. Model scenarios are generated using a system model and by systematic variation of the unknown or uncertain parameters in the model. In this approach, model experts select some of the produced trajectories as scenarios. The third type, formative scenario analysis, combines qualitatively assessed impact factors to a quantitative rating of relations between them. How the rating is carried out depends on the selected method (such as consistency analysis and cross-impact analysis). According to Tietje, the ‘formative’ indicates the generic mathematical structure behind the scenarios, i.e. the mathematics that creates the scenarios from the qualitative/quantitative expert assessments.

The other example is a definition of three historic (and geographic) ‘scenario schools’ (Bradfield et al., 2005): Intuitive-Logic models, La Prospective models, and Probabilistic Modified Trend models. These scenario schools have their own methodological approaches, and they connect scenarios to different purposes or uses in organisations. According to Bradfield et al, (2005), Intuitive-Logic scenarios can serve a wide range of purposes, but the other two alternatives are best suited for particular uses: La Prospective models for strategy development and Probabilistic Modified Trend models for explorative prediction and policy evaluation. The methodological repertoire of these scenario schools is comparable to the categorisation above by Tietje (2005). The intuitive school can be compared with the holistic approach in its informality, even if it utilises completely qualitative reasoning in scenario development, such as brainstorming or thematic clustering or matrices. On the other hand, the holistic approach (and perhaps also model scenario analysis) connects with the probabilistic school due to their use of quantitative model-based approaches and trend extrapolation. Finally, the La

Prospective school defined by Bradfield et al., (2005) is equivalent to the formative scenario analysis as described by Tietje et al., (2005).

The above examples illustrate how taking a methodological approach as a starting point leads to different categorisations, which are simultaneously overlapping and incompatible due to different initial premises in the making of the categorisation. A truly integrative approach is possible to achieve by extending the limited methodological categorisation towards epistemic analysis. In the wider epistemic approach, the question on methods, i.e. how we can know something, is only one of three essential questions. The other two questions deal with reasons why we want to know something and what we can know in the first place. These questions guide our aspiration to first seize the field of scenario–making and then analyse nuclear waste management as a scenario problem.

This report is organised as follows. Chapter 2 provides the needed background information on the nuclear waste repository system and the context of scenarios in decision-making related to nuclear waste management. The remaining chapters (3–5) show the outcomes of our analyses, which aimed to contribute to the following project goals:

1. "*contribute to the advancement of overall safety by distilling 'lessons learned' from several application domains on the uses of scenario analysis in the identification and analysis of uncertainty factors*"
2. "*formulate systematic frameworks and structured approaches which can be deployed to assess the overall safety of nuclear waste repositories*"

To achieve the goals, work was divided into two main tasks. First, we carried out an extensive literature survey to study the scenario approaches of different disciplinary fields. We did a data search from academic journals from four fields: Energy studies, Environmental studies, Risk & Safety analysis and Foresight. We selected the four fields because the scenario method is widely used in these fields, and they are also relevant to the subject field of our study. We carried out a qualitative analysis of almost 400 articles to identify different scenario approaches. The results of the analysis are shown in sections 3.3 and 3.4.

The epistemic approach of our study is manifested in a matrix, which we call the *epistemic scenario framework*. We designed this framework for the literature review, using previous scenario typologies as a source of inspiration. Among the reviewed typologies, two were especially useful (Bradfield et al., 2005; Börjeson et al., 2006). What makes our approach different from previous typologies is that we concentrate on the epistemic perspective of scenarios, which has been absent or at least less explicit in the previous typologies. Our approach, concentrating on knowledge production, enabled us to integrate the different scenario approaches from different disciplinary fields into the same framework.

In the second part of the project, we applied the epistemic approach in the analysis of nuclear waste repository scenarios. We analyse the special characteristics of the nuclear waste repository system and requirements for the scenario analysis as part of the overall safety assessment of the repository systems. This analysis is in Chapter 4. Chapter 5 combines the discussions of the previous chapters. We present our findings from the analysis and present how the epistemic scenario framework may be useful in the analysis of scenario problems and evaluating the needs of a proper scenario approach. In this context, it is important to note that our aim was not to develop new methods but to increase understanding of scenarios as a knowledge-creation field and present the existing scenario approaches. We wish that this work increases understanding of the nuclear waste repository as an application case for the scenario method.

2 The context for scenario development: nuclear waste repository and safety case

This section provides the required background information about the target system of this study. In Section 2.1, we describe the multibarrier disposal concept. Section 2.2 discusses the decision-making context where scenarios are needed in nuclear waste management.

2.1 Description of the nuclear waste disposal system

Nuclear waste can be defined as radioactive waste generated in connection with nuclear energy production or as a result of it. Nuclear waste management covers all actions that are needed to take care of the waste in a safe manner. The end point of nuclear waste management is the final disposal. This is why it is reasonable to do all pre-disposal steps with disposal needs in mind so that the total effort and costs can be minimized.

Nuclear waste management follows the “polluter pays” principle, meaning that waste producers will have to cover all costs related to the planning, preparation and implementation of the nuclear waste management of their wastes. In countries producing nuclear energy, a particular nuclear waste community has emerged, consisting of waste producers, competent authorities, research organisations, legislation and funding arrangements. In Finland, funding arrangements include the State Nuclear Waste Management Fund (VYR), which acts as Plan B in nuclear waste management. As waste producers—following the Finnish Nuclear Energy Act (TEM 2019)—will have to put money into the fund that corresponds to the remaining management costs of their current amount of waste, VYR can cover the waste management even if the waste producers would go bankrupt.

The overall purpose of a nuclear waste management system is to take care of the waste safely. For this purpose, competent nuclear safety authorities have set specific safety criteria that the nuclear waste disposal facility must comply with. In the Finnish case, the Radiation and Nuclear Safety Authority (STUK) has set a radiation dose rate limit criterion (0.1 mSv/a), which is about 3% of the average background radiation dose everyone living in Finlan is estimated to receive annually. The dose rate limit applies to the group of people most exposed to radionuclides from nuclear waste. The corresponding doses to other exposed persons must remain “insignificantly low” (STUK 2018).

Geological disposal is the most extensively studied final option for nuclear waste management, and it is currently considered to be the most viable approach. It is based on the idea of constructing a system of successive release barriers between the waste and the environment where people are living. The multibarrier system consists of engineered and natural (the geologic medium) barriers. The construction and dimensions of the system are defined so that more dangerous waste types require a system that is more heavy-duty.

A nuclear waste disposal facility is essentially *a defence-in-depth system*. This means that its first function is to contain all radionuclides. After the system has lost complete containment, its secondary function is to retard and dilute radionuclide spreading from the facility. Technically speaking, the objective is to design the dimensions of a multibarrier system so that radionuclides released into the human environment always remain on a harmless level. In other words, eternal isolation of waste is not required because the activity of nuclear waste will decrease with time.

Figure 1 shows a schematic picture of the disposal concept KBS-3 developed jointly in Finland and Sweden. Posiva Oy is currently constructing a spent fuel disposal facility called “Onkalo” at Olkiluoto in Eurajoki municipality. It is based on the multibarrier concept. The basic idea is to place complete spent nuclear fuel bundles in containers and bury them in approximately 500 m deep crystalline bedrock. Spent nuclear fuel is one of the most dangerous nuclear waste types because it is highly active and contains long-lived radionuclides.

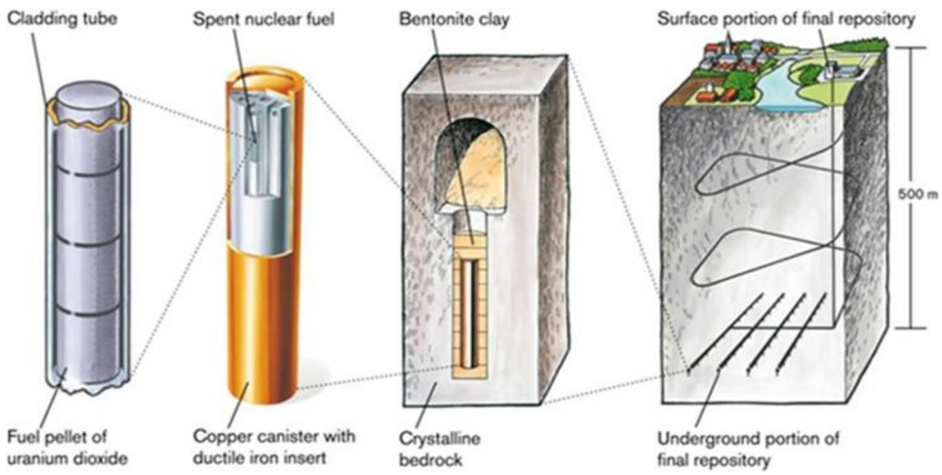

Figure 1. Disposal concept KBS-3 for spent nuclear fuel. (Source http://www.skb.se.)

2.2 Safety case as the demonstration of safety and the role of scenarios

All nuclear waste management facilities have to be licensed. In the licensing process, the safety case is used for assessing the radiological impact of nuclear waste disposal on humans and the environment. In Finland, the government grants a licence for a major nuclear waste managing facility in a stepwise process. The decision procedure includes the following stages: (1) Decision-in-Principle; (2) Construction Licence; (3) Operating Licence; and (4) Closure Licence. After the closure of the repository system, the responsibility for the nuclear waste transfers from the licensee to the state. All decision steps require a safety case, which is therefore developed in an iterative and stepwise manner that takes into account the increasing quantity and level of detail of available information. After the Operating Licence is granted to the disposal facility, the licence holder will have to do periodic safety reviews (i.e. update the safety case) at least once every 15 years (STUK 2018).

As explained above, the *safety case* is an important document at every step of decision-making. Briefly, it contains all safety argumentation with which the licence applicant supports its licence application: the burden of proof lies with the applicant. For every step, the competent authority will review the safety case and provide a statement for decision-makers. The government rests its decision in each step on evaluating whether granting the licence is in the “overall good of the society”. In this evaluation, safety is an important argument but only one of many. Figure 2 illustrates these arguments and the overall decision-making context, including stakeholders involved and the role of the safety case.

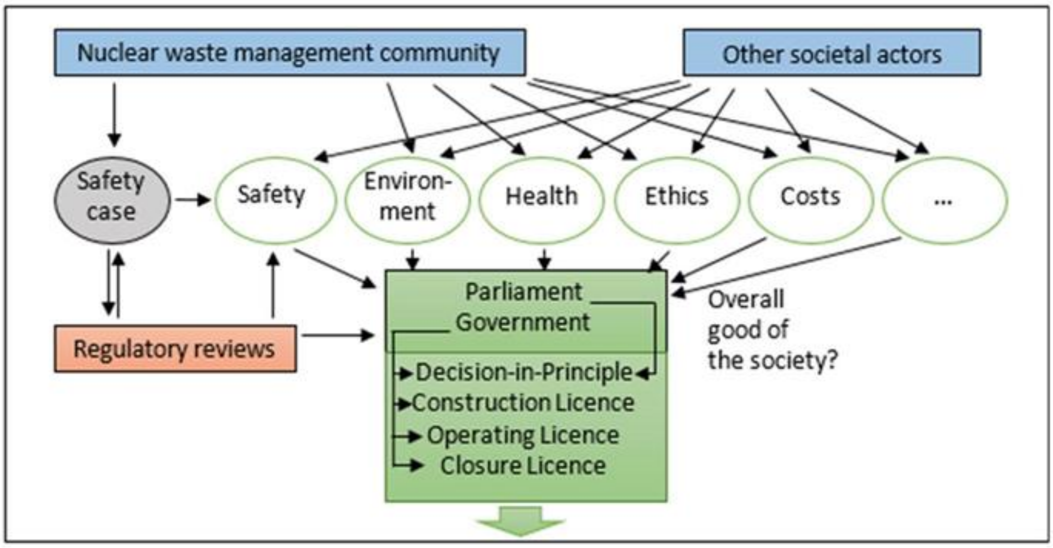

Figure 2 Safety as one argument in decision-making about nuclear waste management. N.B. An iterative and gradually improved safety case is required at all major decision steps (Rasilainen et al., 2019).

The licence applicant, a member of the nuclear waste community, produces the safety case. However, as decisions concerning nuclear waste management are of general interest and discussion on the topic involves actors from other societal spheres, the content of the safety case needs to be adapted and simplified for the context so that it supports overall argumentation and societal discussion. (The arrow from ‘safety case’ to ‘safety’ in Figure 2 indicates this aspect.)

In this context, it is important to see that all actors use a wide range of arguments and their own conceptions on issues. For example, arguments about safety may get different interpretations because safety is an ambiguous concept, and it is used in many areas of technical and scientific research as well as in common language. The radiological safety of a nuclear waste disposal facility may have direct or indirect connections to risk management practices, accident investigation, organisation research and safety culture, public perception of safety, as well as to compliance with regulatory criteria. In addition to different conceptions, the argumentation on radiological safety needs to encounter other arguments, such as costs, ethical considerations and environmental issues in the contest for decision-makers’ attention.

After many years of international collaboration (see, e.g., IAEA 2012, NEA 2012, WENRA 2014), there is currently a relatively broad international consensus on the overall role and contents of the safety case. (See Figure 3 for the main components of the safety case.) The safety case can be considered as an established methodology used in nuclear waste management to estimate the long-term safety of a repository (i.e. the disposal facility). Rasilainen et al. (2019) briefly discussed the possible needs for extending the methodology. These needs were identified mainly in relation to organisational factors, such as the depth and extent of describing and reviewing the management system of the licence applicant to cover the safety culture of the company, for example. Extension need considerations were inspired by lessons learned after the Fukushima accident in 2011, in which the performance of organisations was being studied.

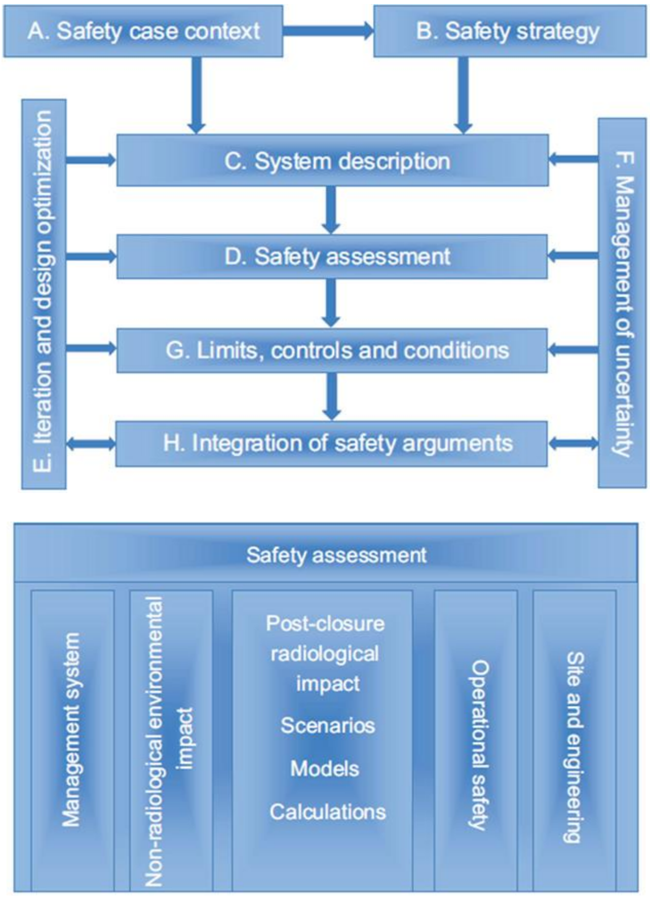

Figure 3. Main components of the safety case and safety assessment according to IAEA (2012). N.B. Scenarios are a vital part of the safety assessment.

Geological disposal will expose the disposal facility to geological processes over geological time scales. Regarding the long-term performance of the disposal facility, the safety case defines specific safety functions for all main components of the disposal system. These safety functions describe how the component is planned to contribute to long-term safety. In order to outline what could happen to the disposal facility in the future, specific features, events and processes (FEPs) are compiled and analysed in the safety case.

The safety case must take into account various unavoidable uncertainties. Methods to be used in the management of uncertainties cover sensitivity analyses, conservative simplifications, and scenarios. Conservative simplification means that, as the complicated nuclear waste disposal system must be simplified in any case, the structural and conceptual simplifications, calculation models and input data to the calculation models are simplified in a manner that overestimates the radionuclide release rates. It requires a lot of expertise and experience, however, to know when one is being conservative.

Scenarios are mainly intended for addressing system-level uncertainties. Uncertainties can be divided roughly into epistemic (knowledge-based) uncertainties, which can be reduced by further research, and aleatory (random) uncertainties, which are irreducible due to the inherent probabilistic variability of some parameters. System uncertainties are often aleatory in nature, and formulating scenarios therefore requires particularly extensive and interdisciplinary expert judgement.

This chapter has given background information about the use of scenarios in nuclear management. In the next chapter, we step aside from nuclear management and explore how scenarios are used in other disciplinary fields. We will return to nuclear waste management in Chapter 4.

3 Framework for understanding the scenario field

This chapter covers the literature review carried out in this study. First, we introduce our methodological approach. In the second section, we develop the epistemic framework for the review. After that, we show the findings of the review, followed by a summary in the last section.

3.1 Methodology: an integrative literature study and epistemic analysis

3.1.1 Research questions for the epistemic analysis

The aim of our study is to integrate the perspectives of different scenario application fields into a comprehensive understanding of scenario practice. This aim is not straightforward, because the scenario method has been applied in very different contexts and different scholarly fields may have a completely different understanding of what scenarios are and how scenario analyses should be carried out. To overcome this abundance of approaches, we started building the integrative view by conceptualizing scenario-making as a knowledge-creation process. In other words, every scenario process, despite the traditions or choice of methods, aims at creating knowledge about the future to inform some action or decision in the present. This starting point led us to develop a methodological approach that we call epistemic analysis.

We started from the three basic questions of epistemology: (1) What can we know? (2) How do we know it? (3) Why do we want to know it? We translated these questions into the context of scenario-making to carry out the analysis of reported scenario studies.

Figure 4 shows (in dotted text boxes) the guiding questions that we used in the analysis of selected scenario studies. Based on the analysis, we aimed at answering the following integrative research questions:

- RQ1 - How does the scenario purpose guide the selection of scenario techniques?
- RQ2 - What kind of scenario approaches can be identified using the epistemic perspective as a starting point?
- RQ3 - Do the application fields differ in terms of scenario approaches?

With our work, we aim to contribute to increasing understanding of scenario approaches and their epistemic dimensions. We wish that the epistemic framework, which integrates the goals and purposes of knowledge production with the methodological approaches, will help readers to evaluate their own scenario problems and guide the selection of the proper scenario approach.

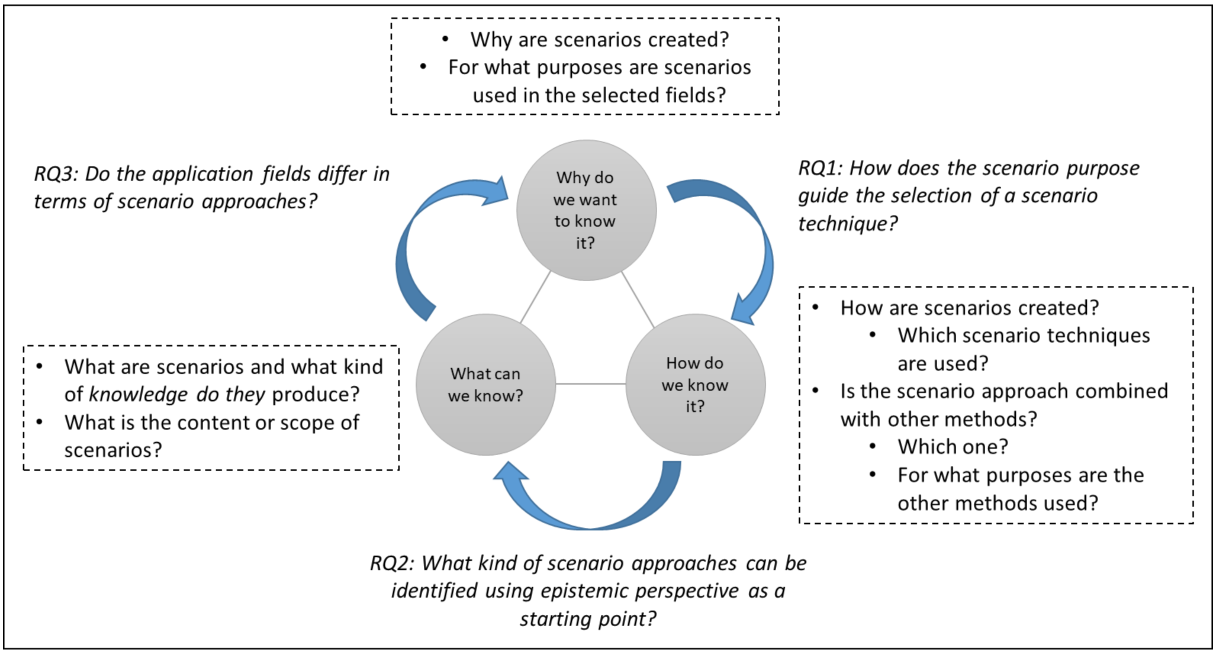

Figure 4. Research questions (RQs) for the epistemic analysis. Questions listed in separate text boxes were used for guiding the analysis of articles.

Our research method is an *integrative literature review* that aims at synthesizing the previous research literature to propose new research directions or models for new understanding. This approach differs from a *systematic literature review,* which is a method widely used within medical and other scientific fields to synthesize and compare evidence from previous studies, especially due to its qualitative approach in synthesis and reasoning. An integrative literature review can also have broader research questions and more open search strategies and selection of source materials compared to a systematic literature review (Snyder, 2019). Torraco (2005, p. 356) defines the integrative literature review as *a form of research that reviews, critiques, and synthesizes representative literature on a topic in an integrated way* so that *new frameworks and perspectives on the topic are generated.* As this definition suggests, critical analysis of the literature and the creation of an integrative outcome that provides new perspectives to the reviewed topic are essential characteristics of an integrative literature review. Torraco (2005) suggests four different forms of such an outcome, which range from the formulation of a new research agenda to different models or metatheories that open new ways of thinking about the topic.

If we apply the conceptualisation by Torraco (2005) to our study, we can see the outcome as a combination of typology and metatheory. The epistemic approach functions as a “metatheoretical lens”, which we use for synthesizing a body of literature across domains (the different scenario application fields) to generate a typology of scenario approaches. In addition to theoretical contributions, we wish this typology to also be useful for practical purposes to anyone wanting to develop scenarios for a given purpose.

3.1.2 Review process

An integrative literature review has three general steps. The first step is to decide on the research design and goals to be able to create a sample for the study. The second step is to analyse the literature to abstract information from it. Finally, one needs to report the findings so that the new conceptions or models are put forward. In the following, we explain how these steps came out in our review process.

Scenarios have been applied since the post-World War II period in various fields ranging from business planning and strategy to environmental and energy studies to policy analyses and transformation processes. This has generated an enormous number of scenario studies and publications on the one hand but also numerous methods and techniques on the other. This abundance of publications and approaches was something that encountered when starting our literature search. At first, we tried to keep the search as general and open as possible and did the search from the SCOPUS database using general scenario keywords. This approach generated data samples from more than 200,000 abstracts. Such a large number of abstracts was not possible to handle within the scope of this study. Therefore, we decided to limit our search to a limited number of relevant journals representing four different scenario application fields. These fields were *Energy studies*, *Environmental studies, Risk & Safety studies* and *Foresight.* These four fields represent areas that are relevant to the nuclear waste management topic while having a strong tradition in using scenario analysis.

We included in the search inquiry the following scenario-related terms: '*scenario method*', '*scenario analysis*', '*scenario technique*', '*scenario planning*', '*scenario identification*' and '*hazard identification*'. We required that at least one of these terms should appear in the title, abstract or keywords of the article. We included in the inquiry the range of different accessory terms combined with the word 'scenario' to cover the different uses of scenarios in different fields. The term "hazard" was also included as a relevant term the in risk and safety field, which may not explicitly use the word "scenario" in their studies.

Table 1 presents the journals selected for our study and the size of the sample. In the beginning, our sample included more than a thousand scientific articles. As this number was still too large for our study, we made another selection round where we emphasised our aspiration to study the practice of scenario-making. Therefore, we defined the selection criteria to recognise the type of articles that we wanted to include in our study. As described in the abstract, we required that the study apply the scenario method to a concrete question or problem, with the scenario method being a central element in finding answers to the question at hand. For example, review articles or theoretical discussions of the scenario method were excluded from the sample at this stage. We also made a time limitation and included only articles from this century so that the samples of different fields would be compatible. This selection process resulted in the final sample of approximately four hundred articles.

Table 1. Journals and number of articles included in the review.

Category	Journal	Original Sample	Selected sample	Publication years of selected articles
Energy	Energy	153	89	2007…2020
	Energy Policy	151	51	2005…2020
	Total	**304**	**140**	
Environment	Journal of Cleaner Production	209	69	2003…2020
	Science of the Total Environment	136	39	2009…2020
	Total	**345**	**108**	
Safety/Risk	Safety Science	51	3	2006…2020
	Risk Analysis	31	6	2002…2020
	Process Safety and Environmental Protection	29	15	2010…2019
	Total	**111**	**24**	
Foresight	Technological Forecasting & Social Change	126	43	2000…2020

Category	Journal	Original Sample	Selected sample	Publication years of selected articles
	Futures	122	38	2003…2020
	Foresight	78	22	2003…2020
	Total	**326**	**103**	
	Total sample	**1086**	**375**	

Figure 5 shows the procedure that we used for extracting information from our data sample. At first, we used the abstracts of articles as the primary source of information. The first step was to identify the purposes of the scenario studies. This step refers to the WHAT aspect of epistemic analysis. In other words, we identified from the abstract the goal or purpose of the scenario study and coded these with NVivo qualitative analysis software. This data was used for grouping the scenario studies into initial groups. At this stage, we had identified 13 types of purposes and one additional unclassified category.

In the second step, we analysed these groups separately, describing the other two aspects of epistemic analysis. We called this step 'descriptive analysis' because the aim was to produce descriptions of the scenario types. At this stage, the initial grouping of scenario purposes was elaborated and further defined so that the final scenario types were defined on the basis of all three epistemic dimensions. Descriptive analysis was carried out by three different researchers. To ensure that the work by different researchers would follow similar patterns, we designed a template for the descriptive analysis. It listed the central questions of interest to be covered in the analysis. Finally, based on the descriptive analysis, we drafted the descriptions of the identified scenario types. We drafted the epistemic scenario framework combining the identified scenario types with findings from a background study of previous scenario typologies. The findings of the review are explained in the following sections of this chapter.

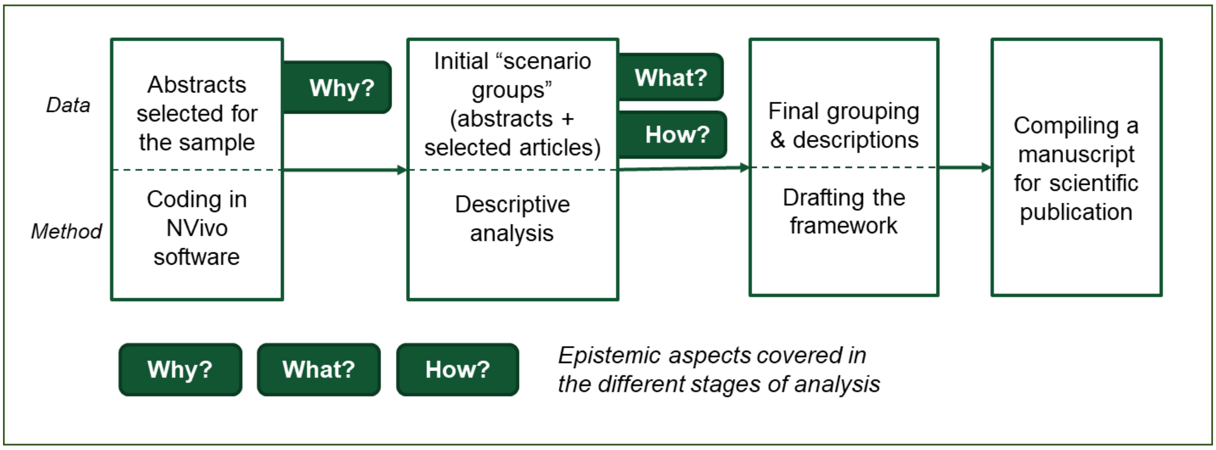

Figure 5. Analysis procedure applied in the review.

This report covers the findings after the descriptive analysis step, including the identified scenario types, their descriptions and the drafted framework. This material will be used for a manuscript of a scientific publication. The publication process will extend beyond the end of the project.

3.2 Developing the epistemic scenario framework

As the aim of our study is to integrate different scenario approaches from different disciplinary fields into the same framework, the first question is 'What are scenarios'? How can scenarios be defined so that it is possible to identify potentially very different scenario approaches and locate them under a single framework? Moreover, what kind of dimensions should such a framework have? To find answers to these questions, we reviewed some already published scenario typologies. Many of the reviewed typologies were published in journals concentrating on futures studies and future-oriented technology assessment. Therefore, these typologies reflect a general understanding of what scenarios are in the field of foresight and futures studies.

It seems that the generally accepted understanding of scenarios is to define them as some kind of storylines that describe potential or possible future events or developments and are used for anticipation or decision-making, as in the following:

- *”--, the typology uses the following broad working definition: scenarios are descriptions of possible futures that reflect different perspectives on the past, the present and the future.”* (Van Notten et al., 2003, p. 424)
- *“A scenario is a story, describing potential future conditions and how they come about, produced for a variety of purposes, e.g. to enable sense making, to inform decision making*. (Wilkinson & Eidinow, 2008, p. 3)

A more precise definition is given by Ducot & Lubben (1980) in the earliest of the reviewed typologies:

- ”*Scenario is a set of potential occurrences which: belong to a certain field of relevance (e.g. world population, energy, or raw materials), relate to a certain time period; and are connected by various kinds of relations (e.g. temporal succession, causality, effectuality, intentionality, instrumentality, and conditional probability) in such a way that an approximation to the whole set can be derived from a subset of basic hypotheses taken from it*.” (p. 51)

Even if the above definition includes the idea of scenarios as “descriptions of possible futures” and the “story-like character” of scenarios, by including the temporal or causal connections into the definition, it is clearly a representation of a different scenario tradition from the other two listed above. Ducot & Lubben (1980) do not define scenario as a descriptive story but as a “set of occurrences” that enables an approximation of future conditions based on the assumptions and hypotheses made in the scenarios. This definition leads to a quantitative understanding of scenario analysis. In other words, scenarios are not storylines but sets of parameters describing future conditions.

Among the reviewed nine typologies, there was only one (Börjeson et al., 2006) that commented explicitly on the two different scenario understandings (qualitative storyline and quantitative set of parameters) and included both of them in the typology:

- “*One of the most basic, although contested, concepts in the field [futures studies] is ‘scenario’. It can denote both descriptions of possible future states and descriptions of developments. We have chosen to use a broad scenario concept that also covers predictive approaches with sensitivity testing, --. The reasons for our choice is that many practitioners use the term in this sense.*” (Börjeson et al., 2006, p. 723)

This interpretation is opposite to that of Wilkinson & Eidinow (2008). As shown above, Wilkinson and Eidinow define scenarios only as descriptive storylines that describe potential future conditions and their emergence and have “several characteristics that differentiate them from other futures practices, such as projections, predictions and forecasts” (p. 3). According to them, these characteristics are: “[Scenarios] are holistic (i.e. multi-dimensional); they are schematic; they come in sets of two or more; and they claim less confidence than other types of future statements” (ibid). These characteristics certainly describe scenarios. However, they are not very strong grounds for excluding a “projective” or “predictive” understanding of scenarios. One could easily attach these same characterisations to the other type of scenarios that understand scenarios as parameter sets. They also “come in sets of” more than one, are multidimensional in the sense that they include several different parameters, and are schematic in their concentration on main connections (not details); and the numeric form of representation does not make them any more "confident" or reliable, but they are still representations of *potential* futures.

To conclude, we do not believe that there are good reasons to make strong or explicit exclusions between the different scenario traditions or approaches. Therefore, we follow the practice-oriented direction stated by Börjeson et al., (2006) and include both descriptive and "numeric" scenario analyses in our framework. This is essential if we want to integrate approaches from various application fields into the analysis. Instead of excluding something, it is more fruitful to try to understand the differences and similarities of these different approaches to generate an overview of the scenario field. This is why the epistemic approach becomes an essential choice for our study.

How would the scenario typologies then inform the epistemic approach? In general, the scenario typologies address three aspects of scenarios: (1) purposes or goals of scenario processes, (2) methodological aspects of scenario processes and (3) scenarios as products. Different typologies put different emphases on these aspects. One can roughly identify two groups. First, those typologies that emphasise the uses or purposes of scenarios or take it as a starting point in typology development (Heugens & Van Oosterhout, 2001; Börjeson et al., 2006; Wilkinson & Eidinow, 2008: Wilkinson et al., 2013). The second group include those that make categorisations that are more comprehensive by integrating the goals with the methodological aspects and contents of scenarios (van Notten et al., 2003; Bradfield et al., 2005; Crawford, 2019).

An interesting finding is that previous typologies pay very little attention to scenario techniques. Saying this, we make a distinction between *method* and *technique,* as proposed in Bishop et al. (2007). By method, we mean a focus on "the steps for carrying out the [scenario] process" (ibid, p. 6), and technique is "the particular *way* in which the steps are carried out" (ibid.). When the methodological dimension is addressed, the typologies mainly cover only processual aspects. An example of this is the typology by van Notten et al. (2003), which has a process design element that includes the type of data (qualitative vs. quantitative), the data collection approach (participatory vs. desk research), the resources of the project (extensive vs. limited) and the institutional constraints in the process (open vs. constrained). The typology does not pay any attention to techniques that are used for scenario construction or ensuring the internal consistency of scenarios. An exception to this pattern is Bishop et al. (2007), who classifies scenario techniques. However, their classification does not connect the techniques to any process goals or purposes, and therefore, it is actually a review of scenario techniques rather than a comprehensive scenario typology.

The most integrative approach is in Bradfield et al. (2005), which identifies three historic "scenario schools" and compares them in an extensive table covering also methodological questions, including a list of techniques (called "tools" in the typology). The identified scenario schools are different from each other, not only on the basis of their historical and geographical origins but also due to their different methodological traditions. Figure 6 shows how Bradfield et al. conceptualise the purposes of scenarios according to two dimensions: first, as an exploration or decision-making tool, and second, as a tool for one-time problem-solving or ongoing continuous activity. As a combination of these two dimensions, they identify four purposes for scenarios: making sense, developing strategy, anticipation and adaptive organisational learning. They also state that the three scenario schools, which they identify in the typology, suit different purposes. The most versatile and informal approach, *intuitive logics scenarios,* can be applied for all purposes, but the formal *probabilistic approach* is predominantly a sense-making tool, and the *La Prospective school*, which has its origins in France and combines formal and informal approaches, is a good tool for strategy development (i.e. once-only activity that aims at closure or decision-making).

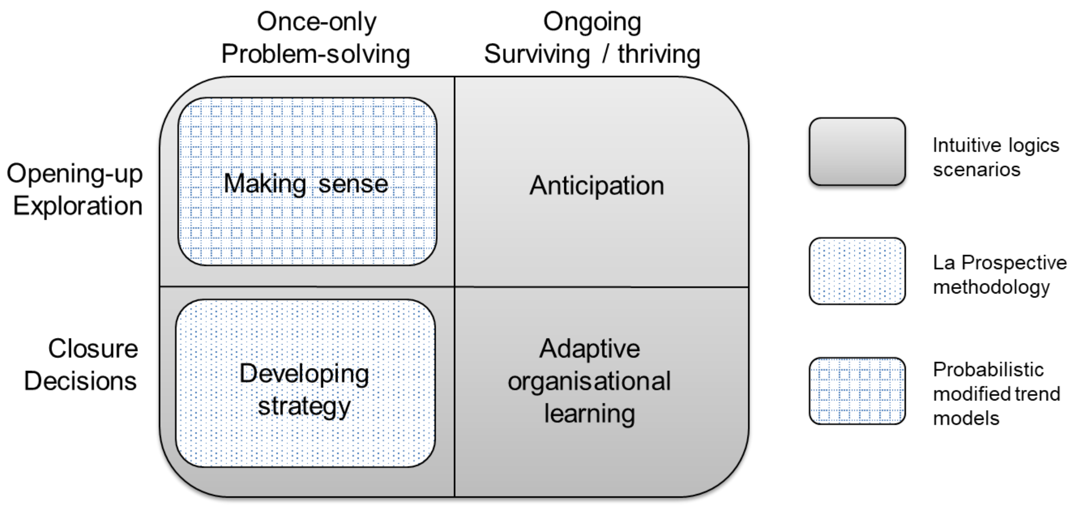

Figure 6. Suitability of different scenario methodologies for different purposes. (Developed from Bradfield et al., 2005)

From the epistemic perspective, the typology by Bradfield et al. is an interesting framework because it connects the purpose of scenario processes (Why do we want to make scenarios?) into methodological approaches (How we can make scenarios?). On the other hand, it has a strong organisational perspective because scenario purposes are connected to the way of organising scenario activity in an organisation. Even if one can connect this aspect to the epistemic dimension of *how* scenario knowledge is produced, it shifts the focus from scenario knowledge per se to the processual level. The distinction between “once-only” activity and “ongoing” activity could describe any form of organisational knowledge production, for example, separating a “once-only quality improvement project” or a “once-only safety analysis of a production process” from the principle of “continuous improvement”.

Another interesting typology from the epistemic viewpoint is the “scenario-tree” by Börjeson et al. (2006). It builds a categorisation of different scenario approaches starting from the questions that “a user may want to pose about the future” (ibid, p. 725). The writers identify three scenario categories: *predictive scenarios* as an answer to the question “What will happen?”; *explorative scenarios* to the question “What can happen?”; and finally *normative scenarios* to the question “How can a specific target be reached?” Each of these categories has two variations (scenario types) that search for answers to the principal question from a slightly different angle. One aspect that defines this angle is how the scenario sees the system under study. Börjeson et al. define *system structure* as “the connections and relationships between the different parts of the system, and also the boundary conditions, which govern a system’s development” (ibid, p. 725). The different scenario types have different views of the system. Table 2 shows our interpretation of the Börjeson et. al. typology from the systemic perspective.

Table 2. Scenario types and their views on the system under study (based on the typology by Börjeson et al., 2006).

Scenario category	**Scenario type**	**How scenario views the system under study?**	**Emphasis of the approach**
Predictive scenarios	Forecasts	Predictions of external factors that are expected to evolve according to certain, already known principles.	On the external environment
	What-if	Investigation of the effects of certain internal factors or external events on the system.	On the system
Explorative scenarios	External	Developments focusing on the factors external to the system, i.e. beyond the control of the system owner or the phenomena steering the system.	On the external environment
	Strategic	Analysis of the effects of internal factors, and external factors directly affecting the system, into the future outcomes of the system.	On the system
Normative scenarios	Preserving	Finding an effective solution or optimal structure for the system to meet targets.	On the system
	Transforming	Finding options that satisfy external long-term targets. The present system structure may be an obstacle to reaching the target.	On the external environment

Thinking about the connection between scenario types and their understanding of the system focus leads us to the WHAT aspect of the epistemic approach. In other words, the question of how different scenario types relate to the system or its environment is connected to the question of *what* is the content or subject of knowledge expressed in scenarios. Therefore, the distinction between *internal* system focus and *external* environment focus is useful for our epistemic scenario framework. Another, almost evident, distinction is between *normative* and *explorative* scenario purposes. This distinction is present in many of the previous scenario typologies (e.g. Heugens & Van Oosterhout, 2001; van Notten et al., 2003, Bradfield et al., 2005, Börjeson et al., 2006). Sometimes this divide is expressed as the distinction between normative and explorative scenarios, or between exploration (producing knowledge) and decision-making (purposeful action). The division between normative and explorative purposes relates to the WHY aspect of the epistemic approach, which is therefore the other dimension of our typology. Figure 7 shows the structure of our *epistemic scenario typology*. As an illustrative example, we have included the six ideal scenario types identified by Börjeson et al. (2006) into our framework. Now, the question for our literature study is, what kind of scenario practices can be found in different application fields and how do they “settle” into the epistemic framework. We move to the findings of our review in the next section.

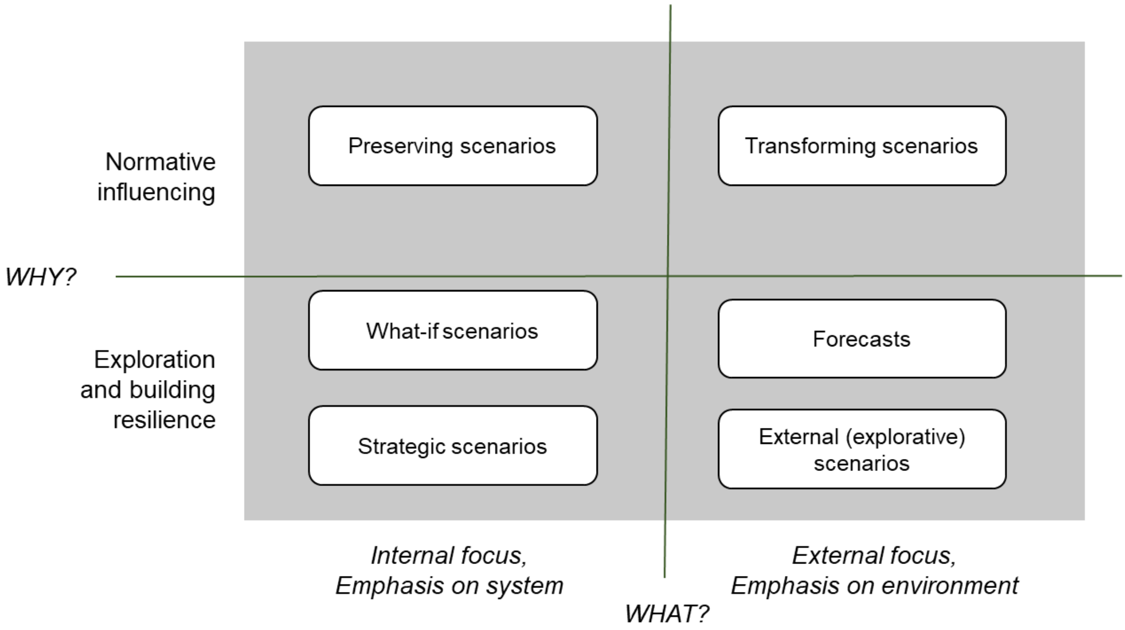

Figure 7. Epistemic scenario framework. As an illustrative example, the figure shows the locations of the ideal scenario types identified by Börjeson et al. (2006).

3.3 Results of the literature study

In this section, we describe the scenario approaches that we identified from the literature. There are four main approaches: Scenario analysis, Safety analysis, Scenario exploration, and Scenario facilitation. We explain all of them briefly in the following.

3.3.1 Scenario analysis

Scenario analysis refers to a quantitative approach that follows “modelling logic”. In our literature sample, it was a common approach in energy and environmental studies. By modelling logic, we mean an approach in which the final result of analysis is created by combining scenarios with modelling. Scenarios represent some possible changes or future options, and they are used as an input for modelling to analyse their consequences. Modelling, simulation or calculation results are then the final result of analysis, and they are interpreted for recommendations or another answer, depending on the subject of analysis.

A typical feature for this type of study was that they may combine both normative and explorative approaches, and sometimes it is difficult to separate these elements in a single study. On one hand, this type of study may have a strong normative starting point. These studies often define their purpose as an assessment or analysis of “emissions reduction potential” (e.g. Guo et al., 2019) or “promoting energy conservation” (Lin & Wang, 2014), or they take some politically defined emission targets as starting points. The aim of the analysis is then to find the optimum that minimizes harmful impacts with minimum cost. However, the overall analysis is carried out in an explorative manner by defining scenarios that represent different “operational alternatives” and are used in the assessment to find out the impacts. Some other studies may start without such a strong normative goal and aim to analyse the consequences of some policies or actions to the system under study. For example, Zhu et al., (2020) studied the effect of policies promoting renewable energies on the retail electricity market using a system dynamic model. These studies may use a similar kind of explorative model-based analysis and sometimes even use similar indicators for impacts, but their aim is to increase understanding of the system and effects of policies on it or to create predictions for the future (e.g. Trost et al., 2017).

For clarity, we identified two types of scenario analysis, even if they do not necessarily appear as ideal types in real-life cases. *Scenario Assessment* searches for the “optimum” for the outcome or compares different scenarios in order to prioritise them. This type of analysis is more normative in nature. *Scenario exploration* does not necessarily have such a normative goal but compares different scenarios to increase understanding of how some factors or changes affect the system. Sometimes these studies may also have a predictive element in how they present the scenarios and report the results of analysis as projections of the scenario impacts. Both of these types produce their outcomes by combining scenarios with another model that describes the system under study and uses modelling techniques suitable for analysing the phenomena of interest. This model has a central role in the analysis, as it produces the information that interests the analysts or users of the information.

What are scenarios, and how do they relate to the other dimension of our epistemic framework? As scenarios are integrally connected to the impact assessment or modelling step in scenario analysis, the content of scenarios need to be quantified. Therefore, one could describe scenarios as a set of parameters that are used as input for another model. In other words, scenario parameters represent the uncertainties or factors that are subject to change. They may describe various future directions, e.g. in technology development or the use of certain technologies or operational policies, the need for some resources (raw materials, energy), or policy options (e.g. implementation of carbon trading schemes). In terms of the internal vs. external division, scenario parameters can include both internal factors, i.e. parameters describing the system (such as the type of technology used or energy efficiency of different technologies) and external factors that have an effect on the system (e.g. implementation of a certain policy). However, we can claim that the main focus of scenario analysis is on the system because scenarios together with impact modelling create the content of analysis: Which changes we want to study (scenarios) and which impacts fof or on the system we are interested in (model).

It was common that abstracts included in this type often just stated that “this study uses scenario analysis” or “system was studied under four scenarios” and went on reporting the main findings. Sometimes abstracts reported the main factors included in scenarios or explained that a certain number of scenarios “were developed” and gave their names indicating the main factor of the scenarios, as in the following example: “*Four future scenarios are developed; business-as-usual (BAU), current-policy (CP), strong-growth (GRT) and green-development (GRN). The BAU scenario indicates that environmental impacts may double without additional improvement options. The CP scenario shows that current plans to increase palm oil production would considerably increase environmental impacts*” (Saswattecha et al., 2017).

As the construction of scenarios is not discussed in more detail in an abstract, it creates an impression that scenario creation is an unproblematic selection of parameters representing those changes that are known to be interesting for the study. Actually, the development of the model is often the major content of the paper, and it is possible to find examples of different modelling approaches. Examples range from agent-based modelling (Luo et al., 2009) and system dynamic modelling (Zhu et al., 2020, Kotir et al., 2016) to tailored modelling approaches (Levesque et al., 2018) and the use of general energy system modelling approaches, such as MARKAL/TIMES (Das et al., 2018; Panos et al., 2016) or LEAP for developing countries (Awopone et al., 2017; Luukkanen et al., 2015; Mustonen, 2010).

Sometimes scenario analyses apply approaches where scenarios are contextualised with narrative storylines that describe future uncertainties or alternative futures. These scenarios are developed in a step-wise scenario process, defining and evaluating critical factors affecting the system and following some logic in the narration (e.g. Awopone et al., 2017). However, for evaluating the impact of the scenarios, these storylines need to be quantified. Another approach is to construct scenarios as combinations of some features or parameters describing the system or the subject of the scenario. For example, Yokokawa et al. (2008) developed consumer behaviour scenarios related to food consumption and packaging disposal as combinations of choices in six consecutive actions.

In studies applying a life-cycle assessment (LCA), scenarios usually mean alterations of system parameters that analysts want to include in the analysis. For example, Guo et al. (2009) study the environmental impacts of aluminium production using nine scenarios, of which two concentrate on production growth, four on technological progress and three on energy system changes. The analysis approach in this kind of study follows a similar logic as what-if scenarios. What if we change this system parameter? What are the environmental consequences of this change? The goal of the analysis to find out which scenarios create the smallest impact and how different changes affect the impacts from different life-cycle stages. In this type of model-based assessment approach, explorative analysis and normative goals of knowledge production are intertwined.

3.3.2 Scenario exploration

The scenarios in this group deal with uncertainty, unpredictability and the unknown. The scenarios fundamentally explore alternatives of something that could exist in the future. The future is not determined but rather open for exploration and future-oriented action. In the scenarios, change is usually characterized as non-linear, dynamic and complex. As Merrie et al. (2018) state, scenarios can help 'develop a capacity for dealing with the unknown and unpredictable, or the unlikely but possible'.

Most often, the scenarios themselves are qualitative narratives describing plausible and consistent future states. The narratives are typically compact, ranging from a single paragraph to one page in length. The scenarios often have a name that is easy to remember and refer to in conversation. The number of scenarios is typically from three to five. In the Kaufmann and Lohaus (2018) article about scenarios for the future of transatlantic relations, the scenarios are called 'Pick and choose', 'Europe takes the wheel', 'Rally ‘round the flag' and 'Rules for the future', and the scenario narratives are about one page long. One part of the 'Europe takes the wheel' scenario narrative illustrates a typical way of writing qualitative, explorative scenarios:

'Following the Brexit shock, EU leaders agree on a communications and legitimacy offensive to fend off populist movements in the wake of Brexit. Europe's foreign policy apparatus evolves. As the EEAS gains experience and fine-tunes its working relationship with member states and the EU Commission, the changes intended by the Lisbon treaty begin to materialise in practical terms. The center of gravity for day-to-day foreign policy moves to the European level, not least because EU members are happy to consolidate expensive foreign operations.’

The scope of this group's scenarios is usually broad, taking into account multiple dimensions in the external environmental, such as environmental, economic, social and technological aspects. Data sources can be qualitative and quantitative, even though the thinking process and the scenarios are primarily qualitative. If quantitative data is used, it is applied alongside qualitative data or as a complementary source, but not alone. For example, in the study of Varho and Tapio (2013), the scenario technique combines qualitative and quantitative methods by using Delphi, cluster analysis of numerical material, qualitative content analysis on interviews and a futures table. According to the authors (Varho & Tapio, 2013), combining qualitative and quantitative materials and including many kinds of experts are trends in scenario-making.

In another multi-method study, Alizadeh and Soltanisehat (2020) integrate several foresight methods—including Delphi, scenario planning, MICMAC and cross-impact analysis—to envision alternative futures of the design and manufacturing industry. In an article about transition pathways for hydrogen energy, Will McDowall (2014) suggests using both modelling approaches and narrative storyline scenarios, as each has shortcomings if used alone. As Merrie et al. (2018) note, in recent years, there has been an evolution towards using diverse creative narrative techniques such as incorporating science fiction prototyping.

Even in systematically formulated scenario processes, intuition, creativity and subjectivity can play a significant role when using an expert evaluation during different parts of the scenario-building. In the approach of Kuzmina et al. (2019), industry organisations, experts, end-users and academic stakeholders are engaged in exploratory scenario-planning on the future of the fast-moving consumer goods industry within a circular-economy context. The paper describes scenario planning as 'a pre-strategy research activity of exploration' (Kuzmina et al., 2019). As the former examples demonstrate, scenario methods are hardly ever used individually, but rather as a part of a more extensive process. In every article of this group, the process of creating scenarios is simultaneously unique and recognisable, which leads to an assumption that there is much flexibility in the scenario techniques of the foresight field. In terms of terminology, processes, methods and outcomes, the scenario group is uniform and recognisable. Scenario exploration has two significant application areas—corporate strategy and policy planning.

Explorative scenarios focusing on business strategies

Strategic management is a crucial domain for explorative scenarios. The scenarios are built to support top-management decision-making, strategic planning and different areas of business development. For example, in the article by Roubelat (2006), scenario planning is meant to challenge strategic paradigms and allow the organisation to rethink its internal and external processes through networking. In a case study concerning the Russian truck industry (Winkler & Moser, 2016), scenarios are used to cope with strategic uncertainty. In the analysis of Ramírez, Österman, and Grönquist (2013), scenario planning is a dynamic capability that helps to frame managerial attention.

In a business context, the scenario process and the project scope are usually more focused than explorative scenarios in other contexts. The scenario process may consist of a couple of workshops with the management team in addition to environmental scanning done as desk research. Other methods mentioned in the articles include interviews, trend reviews, Delphi, morphological analysis, PEST, cross-impact analysis, MICMAC, system dynamics, strategic radars, interpretative structural modelling and repeated cross-impact handling. Methodologically, there is no significant difference from other forms of explorative scenarios. The scenario processes usually combine multiple methods that also provide data for scenario formulation.

Scenario creation can also be a part of continuous foresight activities. Ramírez, Österman, and Grönquist (2013) describe Statoil's scenario activities led by the corporate strategy team's organisational scenario unit. More than half of the group management participated in the scenario-planning process, and an external consultant was used to provide content and facilitation (Ramírez et al., 2013). Statoil has regularly produced scenarios since the 1980s.

The 'scenario product' is typically a relatively short narrative describing a future state with business implications. The scenarios are usually explorative, but they can also be normative in the sense that they include a business goal or the company is an active actor pursuing a particular future in the scenario.

Explorative scenarios in policy planning

The policy-related foresight scenarios address significant policy issues that require analytical future directions, debatable alternatives and viable decision-making options. For example, Talberg, Thomas, and Wiseman (2018) describe geoengineering as 'a high-stakes policy issue that calls for research and debate that is pluralistic, reflexive and socially accountable'. The scenario process helps 'focus governance discussions around key issues' (Talberg, Thomas, and Wiseman, 2018). In the article by Bierwisch, Kayser, and Shala (2015), civil security is 'a major issue on the European policy level', and the research has 'a challenge-oriented policy perspective'. The importance of the policy issue directs the research focus.

Compared to business-related scenarios, the scenario processes in policy are usually broader in the sense of the system scope and stakeholders involved. The policy issue may concern an entire industry or an international policy issue. For example, Raele et al. (2014) construct scenarios for the ethanol industry in Brazil, and the contribution of the paper is meant to support the development of public policy and be a tool for decision-makers in the energy sector.

The methods in policy scenarios are typical for foresight processes: scenario matrixes, scenario archetypes, environmental scanning, expert interviews and workshops. For example, in the article by Amorim Varum et al. (2011), scenarios for hospitality and tourism are created through an intuitive-logical process. Four alternative scenarios are developed in three workshops, and the scenarios are identified based on the dynamics of key forces and trends. As in business strategy, the scenarios themselves are relatively short storylines. As Talberg et al. (2018) note, they can be stories of the future from now until then, or snapshots of a future situation.

3.3.3 Scenario facilitation

Bringing people together, facilitating interaction and encouraging debate are the main purposes of this group's scenario process. The lack of collaboration may be the challenge, and scenario methods are considered to be the solution. Social interaction in scenario projects is crucial, and the role of the documented outcome is relatively minor. The chosen methodologies emphasize collaboration, participation, stakeholder engagement and inter-organisational co-operation. Even though the interaction is highlighted in this group, most scenario processes, especially in the foresight field, include social collaboration to some extent.

For example, in the article by Folhes et al. (2015), the participatory scenario method is used to allow dialogue between stakeholder representatives, government organisations and communities. In a similar vein, Zegras and Rayle (2012) note that scenario planning is for developing a long-term strategy and potentially strengthening organisational networks and encouraging collaborative action. In multi-organisational contexts, scenario approaches have been used to engage stakeholders in discussing issues of mutual importance and gain their support for possible future responses (Soetanto et al., 2011). In the article by Barker, Cox, and Sveinsdottir (2011), scenario methods are used to serve as the basis for policy recommendations and to help experts and the stakeholder network discuss a shared vision of the future of the field.

In the article abstracts, the methods and techniques may not have been outlined in detail, but the focus is rather on the social process of scenario formulation. The methods are typical for foresight projects; they include different kinds of workshops, backcasting, narrative construction, causal maps, prospective games, the six pillars approach, decision analysis, environmental scanning, trend-impact analysis and cross-impact analysis. Nevertheless, the primary methods should allow for the participation and interaction of several people. The social process also produces the data for the scenarios, such as the key drivers for a scenario matrix or a cross-impact table. In conclusion, Talberg et al. (2018) emphasize that an essential aspect of the scenario development process is to create an ‘agora’—a domain of primary knowledge production through which people enter the research process and where knowledge is embodied in people, processes and projects.

The scenarios' approach is usually explorative, and in this sense, it follows the tradition of scenarios in the foresight field. The focal issue to be explored can be clearly defined, but the possible, alternative futures for the issue are open. For example, the case study by Zahraei, Kurniawan, and Cheah (2019) is about urban mobility in Singapore in 2040. But the transportation system is considered to be complex and evolving, and the future cannot be projected by simply extrapolating trends. The authors propose a participatory process that includes environmental scanning, expert interviews, focus group discussions and technology scanning (Zahraei et al., 2019). Two scenarios are produced in the process. As an example, an extract from the scenario narrative 'Shared World' depicts a mobility system based mainly on sharing models:

‘In the Shared World, people have embraced community living and shared-resources lifestyle featuring two key aspects: shared mobility and multi-zone districts. Shared mobility is an innovative transportation strategy that enables users to gain short-term access to transportation modes on an as-needed basis. Examples of shared mobility include various forms of car sharing, bicycle sharing and ridesharing. Multi-zone districts are an overhaul of the current land-use plan that fundamentally change travel patterns, reducing cross-island travel for city dwellers.’ (Zahraei, Kurniawan, and Cheah, 2019.)

In the group's case studies, the scenarios are typically relatively short narratives, depicting future worlds in an accessible way. The number of scenarios is most often from three to five, as in the explorative scenarios. Collaborative approaches can also help in implementing the scenarios. In the Soria-Lara and Banister (2018) article, collaborative backcasting is used in bridging 'the conceptual elegance of the scenario approach with the practicalities of implementation' through a participatory approach in which different stakeholders take an active role in building scenarios, identifying policy measures and evaluating pathways.

The focus on collaboration and interaction makes this scenario group distinguishable, even if the scenarios' theoretical and methodological background is in the same tradition as in the group of explorative scenarios.

3.3.4 Safety analysis

The scenarios of this group deal with some sort of analysing safety issues and/or identifying hazards in safety-critical systems. These groups involve both explorative and normative elements. We consider the “Hazard identification” subgroup as being more explorative in nature since the overall aim could be interpreted as keeping an open mindset and involving diverse perspectives to identify a broad spectrum of hazards and a combination of factors that may potentially unfold into an unwanted chain of events. The generic “Safety analysis” group of articles represents a more normative perspective since the scenario process is done in a safety-critical and often highly regulated domain in which operations are subject to strict regulatory requirements. That is, the scenario development eventually aims at ensuring and improving safety as an overarching priority, and there is a normative basis against which the value of scenarios can be measured and justified.

Safety analyses with scenarios generally aim at supporting decision-making in terms of identifying, prioritizing, assessing, mitigating and managing risks, and understanding hazards in complex safety-critical, large-scale systems. Overall, scenarios provide information for identifying potential vulnerabilities and enhancing the safety and reliability of such systems in the long-term. The objectives of the scenarios in this group of articles can be characterised by a focus on capturing changes in the internal and external environment, exploring potential latent issues and combinations of factors that can bring about a chain of events with safety significance that needs thorough consideration. For example, in a study by Ulusçu et al. (2009), scenarios are developed to capture changing conditions, e.g. in the technical system as well as in the surrounding wider environment, including relevant geographical, meteorological and traffic conditions in order to provide input for the developed risk model. According to Baldissone et al. (2016), scenarios identify top events and evaluate in more detail the plant behaviour in the event of failure.

Haimes et al. (2002) argued that a scenario’s objective is to identify, prioritise, evaluate, and manage risks. They proposed eight phases for filtering and ranking of discrete scenarios: Phase I, Scenario Identification: A hierarchical holographic model (HHM) for risk identification is developed to describe the system's 'as planned' or 'success' scenario. Phase II: Scenario Filtering: The identified risk scenarios are filtered according to the responsibilities and interests of the current system user. Phase III: Bi-Criteria Filtering and Ranking. Phase IV: Multi-Criteria

Evaluation. Phase V: Quantitative Ranking in terms of likelihood and consequence. Phase VI: Risk Management, involving identification of management options for dealing with the filtered scenarios, and estimating the cost, performance benefits and risk reduction of each. Phase VII: Safeguarding Against Missing Critical Items—performance of the options selected in Phase VI are examined against the scenarios filtered out during phases II to V. Phase VIII: Operational Feedback—to reflect the experience and information gained.

Scenarios in this group are produced by using system-level data, historical data, holistic thinking, accidents, consequences, quantitative analysis (mathematical analysis, modelling techniques) and qualitative input (subject-matter experts' opinions) (e.g. Ulusçu et al., 2009). In terms of scenario techniques, hierarchical holographic modelling (HHM) is a concrete holistic philosophy or methodology used by Haimes et al. (2002). This methodology aims at "capturing and representing the essence of the inherent diverse characteristics and attributes of a system—its multiple aspects, perspectives, facets, views, dimensions, and hierarchies". The term holographic refers to the desire to have a multi-view image of a system when identifying vulnerabilities (as opposed to a single view or a flat image of the system)" (Williams, 2020).

Other techniques include approaches such as recursive operability analysis (ROA) for hazards evaluation and safety analysis, fault trees (extraction and quantification), and carrying out integrated dynamic decision analysis (IDDA) for risk analysis (Baldissone et al., 2016). In the study by Ulusçu et al. (2009), safety risk analysis is performed by "incorporating a probabilistic accident risk model into the simulation model. A mathematical risk model was developed based on probabilistic arguments regarding instigators, situations, accidents, consequences, and historical data, as well as subject-matter expert opinions."

Subcategory "Hazard identification"

The scenarios of this group deal with identifying hazards or anything that could potentially cause harm. Overall, the goal of scenarios in this group is hazard identification as a means for risk assessment and management and eventually accident prevention. Hazard scenarios can be seen as a knowledge-based tool for process industries to screen hazards and conduct rapid risk estimation (Aziz et al., 2019). Most often, the scenarios in this group represent a chain of events that need to be carefully identified and elaborated in order to assess and mitigate possible hazards, manage risks, define adequate measures and prevent incidents and accidents. In addition, as framed by Bubbico et al. (2018), the scenario is also about capturing possible negative interactions between the system and its surrounding environment.

Paltrinieri et al. (2014) pointed to atypical accident scenarios, i.e. scenarios not captured by common HAZard IDentification (HAZID) techniques because of omissions, errors or lack of knowledge. There is evidence that the consequences of atypical events may far exceed those of the worst-case reference scenarios. In the case of new and emerging technologies, potential hazard identification allows for the proactive adoption of safe design principles to eliminate, prevent, control or mitigate them (Paltrinieri et al., 2014). Wilday et al. (2011) also deal with emerging risks using carbon capture and storage (CCS) as an example. A risk assessment of the CCS process "needs to include both short-term potential accidents from capture, transport or injection, as well as very long-term risks from storage". Therefore, a scenario, in this case, should consider risks both for short-term and long-term perspectives.

Scenarios in this group aim at capturing changing conditions in complex and dynamic safety-critical and high-risk systems, providing input for the risk model development and proposals for risk mitigation (Ulusçu et al., 2009); identifying the most important predictable dangerous conditions and suggesting adequate mitigation actions (Bubbico et al., 2018); defining adequate safety barriers (Vignes et al., 2012); and risk analysis and estimating the consequences of undesired events in terms of severity and extent (Baldissone et al., 2016). According to Paltrinieri et al. (2014), scenarios are means for the identification of emerging risks, dynamic risk assessment, risk management and preventing accidents by taking into account new risk notions and early warnings. Jain et al. (2018) indicated that the “hazard analysis method for a complex socio-technical system, such as a process plant, should incorporate the following characteristics: consideration of all system components (e.g., processes, human operations, equipment, instruments, and control systems), all plausible deviations, a multi-disciplinary team, and proper documentation.”

In a study on risk assessment of the ignitability and explosivity of aluminium nanopowders in an industrial plant, Vignes et al. (2012) conducted a specific risk analysis to assess the fire and explosion risks of such materials. The hazard identification and the consequence-modelling steps—especially the quantification of the likelihood and consequences—have been specifically designed. In this group of articles, such “designed” hazard identification indicates the importance of understanding the specific hazards in the given context or sociotechnical system. Hazards in the process industry are different from hazards in aviation; and although accident causation models show that similar patterns may unfold, understanding the specificity and contextualisation of hazards is critically important for ensuring safety.

Data sources for developing the scenarios in this group can be both qualitative, quantitative or semi-quantitative. For example, in the study by Aziz et al. (2019), probability information from expert knowledge and historical data have been used. Moonis et al. (2010) used semi-quantitative risk assessment by applying top-down HAZID brainstorming, consequence-modelling using commercially available software, and the use of a risk matrix to conduct a risk assessment of the commercial-scale supply chain of hydrogen fuel. A multi-disciplinary team should be involved in the hazard identification process, and the management system should be part of hazard analysis, including the process safety culture and leadership, operational discipline and process safety systems, as highlighted by Jain et al. (2018).

Regarding the system scope in the hazard identification group of articles, there is a system or process that is analysed in hazard identification. Also, the interaction of this system or process or equipment with the larger environment is considered to be within the scope. It may be an explicitly defined existing technological system, such as an industrial plant of aluminium nanopowder production (Vignes et al., 2012), plant (Baldissone et al., 2016) or an emerging system, such as Carbon Capture and Storage, CCS (Wilday et al., 2011) or the transport and storage of hydrogen as fuel (Moonis et al., 2010). It is also possible that the system is described more generally, for example, as a complex socio-technical system (Jain et al., 2018). The focus may also be explicitly on the interaction between the technological system and its surrounding environment (Bubbico et al., 2018). It could be a broadly defined and dynamic system, such as vessel maritime traffic in the Strait of Istanbul, including changes in the surrounding geographical, meteorological and traffic conditions (Ulusçu et al., 2009).

Regarding scenario techniques, hazard identification may be presented as a step in a more extended risk assessment process. In these cases, hazard identification is combined with other methods, e.g. consequence modelling (Vignes et al., 2012; Moonis et al., 2010); Dynamic Risk Assessment (DRA) methods (Paltrinieri et al., 2014) or the use of a risk matrix (Moonis et al., 2010). Cameron et al. (2017) argued for applying experience and historical data, combined with a Bayesian network, hazard and operability studies (HAZOP) and failure mode and effect analysis (FMEA). Paltrinieri et al. (2014) suggested a synergy of two specific techniques for hazard identification and risk assessment—the Dynamic Procedure for Atypical Scenarios Identification (Dy PASI) and the Dynamic Risk Assessment (DRA) methods. As long as there is a good safety culture in the organisation, such synergy allows for collecting risk notions related to the plant, equipment and materials that can be used to dynamically enhance hazard identification and real-time risk assessment. Paltrinieri et al. (2014) conducted HAZID analysis by means of two different approaches—'top-down' and 'DyPASI'. Bubbico et al. (2018) focused on hazardous scenario identification for Li-ion secondary batteries. They used Failure Modes and Effects Analysis (FMEA) to identify the largest number of dangerous scenarios associated with the use of these systems.

In this group of articles, the scenario methods include established and standardised approaches, such as Bayesian Networks (to identify hazards and their pathways along with probabilities), Dynamic Procedure for Atypical Scenarios Identification (Dy PASI), Failure Modes and Effects Analysis (FMEA), Resilience-based Integrated Process Systems Hazard Analysis (RIPSHA), Hazard and Operability (HAZOP) study, HAZard IDentification (HAZID) techniques, high-level hazard identification (Wilday et al., 2011a), bow-tie diagrams, Recursive Operability Analysis (ROA) (Baldissone et al., 2016) and Resilience-based Integrated Process Systems Hazard Analysis (RIPSHA) (Jain et al., 2018). For example, Aziz et al. (2019) used the Semantic web-based Web Ontology Language (OWL) to capture knowledge about unwanted events in the process industry. Then they transformed the resulting knowledge model into a Probabilistic-OWL (PR-OWL) –based Multi-Entity Bayesian Network (MEBN). Furthermore, MEBNs produce Situation-Specific Bayesian Networks (SSBN) to identify hazards and their pathways along with probabilities. Xin et al. (2017) called for “real time hazard identification” since new information or evolving conditions cannot be easily incorporated into already identified hazards. They developed a new methodology to map hazard scenarios into a Bayesian network model. To capture both short-term and long-term risks in emerging technology, Wilday et al. (2011b) utilised DyPASI methodology for taking into account atypical (not usually identified) events during hazard identification, a methodology for including the time dimension in a risk assessment, and life-cycle approaches for risk management and communication.

From the perspective of organisational future-readiness, safety culture as an organisation’s potential for safety (Reiman and Oedewald, 2009; Oedewald et al., 2011) points to a holistic set of organisational capabilities (assumptions, attitudes, values, competences, structures and systems) needed for developing comprehensive scenarios. However, from the articles scoped for this review, only one mentioned safety culture (Paltrinieri et al., 2014). Overall, in both groups of articles, the scenario process can be characterised as systematic and comprehensive, taking into consideration the dynamics of the system. This shows in the widespread use of well-established and standardised methods of analysis. This could be related to the fact that safety-critical industries, such as the process industry, oil & gas, nuclear, aviation, etc., are strictly regulated domains, and there are specific regulatory requirements, industry standards and expectations for high-quality and continuous improvement that guide the process of hazard identification, risk assessment and safety analysis as well.

3.4 Scenario approaches in the epistemic framework

In our literature review, we identified four main scenario approaches with a few sub-categories. Figure 8 shows where these approaches are located in the epistemic framework. The framework has two dimensions. The vertical dimension deals with the purpose of scenarios and separates normative aims from exploration. Normative goals can be connected to such aims as finding optimal designs for some systems in terms of minimizing harmful consequences or finding a shared goal or desired pathways for future development. Exploration, on the other hand, is connected with preparing for the future and exploring possible future trajectories for a better understanding of how today’s decisions and actions affect the future. The horizontal dimension takes a systemic perspective on scenarios and conceptualises the scenario content in terms of whether the focus is on the system (left) or its environment (right).

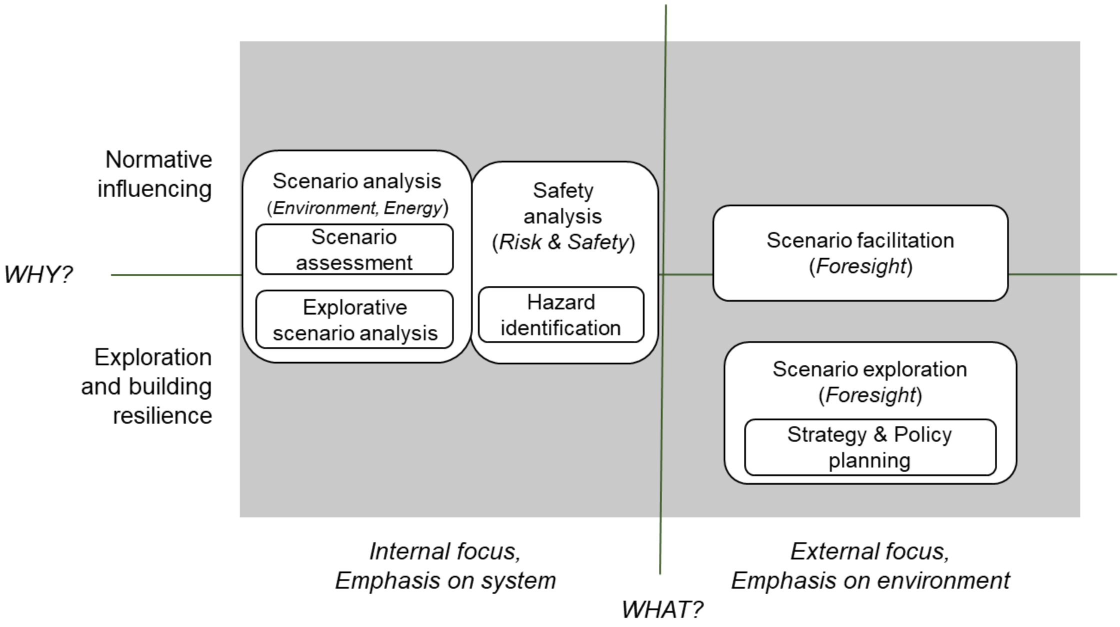

Figure 8. Epistemic scenario framework and the identified scenario practices. The application field in which the practice is prevalent is mentioned in brackets.

In the analysis, we first identified the purposes of the scenario studies—how the authors described (in the article abstracts) the connection between the scenario method and the knowledge-creation activities or goals. In the course of analysis, this classification merged into four major scenario approaches with some additional subcategories. The different disciplinary fields seemed to have well-established approaches in their scenario studies. The fields of energy and environment studies differed from the risk and safety field and foresight. Next, we briefly describe the scenario approaches.

- *Scenario analysis* is the scenario approach that appears mostly in the field of energy and environment studies. Scenario analysis applies quantitative "modelling-logic", which uses scenarios as the input for an assessment model or other type of model that quantifies the impacts or consequences of changes described in scenarios. The knowledge creation process is typically expert-driven and requires knowledge of the subject field and also the modelling or assessment approach applied in the study. These studies tend to blend normative and explorative approaches in their goals and the way that the analysis is carried out. It may be difficult to separate these aspects in single scenario studies, but the overall knowledge production goal and interpretation and presentation of the results can emphasize one of the aspects. Therefore, we identified two variants of scenario analysis—normative *Scenario assessment* and *Explorative scenario analysis*.
- *Safety analysis* refers to a scenario approach that appears mostly in safety and risk studies. The safety analysis and hazard identification group involve both explorative and normative elements. Exploration refers to supporting safety imagination in dealing with a broad spectrum of hazards and a combination of factors that may potentially unfold into an unwanted chain of events. The normative aspect is evident in that scenario development eventually aims at ensuring and improving safety as an overarching priority in accordance with safety requirements and standards. The knowledge creation process is typically expert-driven and requires knowledge of the specific safety-critical context. Safety analysis with scenarios generally aims at supporting decision-making in terms of identifying, prioritizing, assessing, mitigating and managing risks and understanding hazards and connections for identifying potential vulnerabilities in complex high-risk socio-technical systems. Data sources for developing the scenarios in this group can be both qualitative, quantitative and semi-

quantitative. Scenario methods include established and standardised approaches for safety analysis and hazards identification. Traditional methods are applied and new methodologies are developed, for example, to map hazard scenarios onto network models or to capture the risk pathways of emerging technology. Overall, a scenario process when it relates to safety analysis and hazards identification can be characterised as systematic and comprehensive.

- *Scenario exploration* typically appears in futures and foresight studies and deals with uncertainty, unpredictability and the unknown. The scenarios explore alternatives to something that could exist in the future. The future is not determined—it is open to exploration and future-oriented action. Change is depicted as non-linear, dynamic and complex. The scenarios themselves are qualitative, creatively written narratives describing plausible and consistent future states. The number of scenarios is typically from three to five. The scope of the scenarios is broad, taking into account multiple dimensions in the external environment. Data sources can be qualitative and quantitative, even though the thinking process and the scenarios are typically primarily qualitative. Strategic management is a critical domain for explorative scenarios. The scenarios are built to support top-management decision-making, strategic planning and business development. In this context, the scenario process is usually very focused. Another critical domain is policy planning, in which scenarios address significant issues that require analytical future directions, debatable alternatives and viable decision-making options.
- *Scenario facilitation* brings people together, coordinates interaction and encourages debates. Scenario facilitation is typical in the field of futures and foresight studies, but participatory approaches occasionally appear in other fields, too. Lack of collaboration may be the challenge, and scenario methods are seen as a solution. Interaction in scenario projects is crucial, and the role of the documented outcome is relatively minor. The chosen methodologies focus on collaboration, participation, stakeholder engagement and inter-organisational co-operation. The methods are typical for foresight projects, but the primary methods should allow the participation and interaction of multiple persons. The focus on collaboration and interaction makes this scenario group distinctive, even if the scenarios' theoretical and methodological background is in the same foresight tradition as in the group of explorative scenarios.

4 Nuclear waste repository as a scenario problem - epistemic analysis

In this chapter, we apply the epistemic analysis framework to nuclear waste repository scenarios. In sections 4.1–4.3, we approach nuclear waste repository scenarios using the same questions that previously guided our analysis of scenario studies. First, we ask why scenarios are needed in the long-term safety assessment and analyse the decision-making context. Second, we direct our attention to the expectations of the scenario content—what nuclear waste repository scenarios should cover and what they are about. And third, we take an overview of how the nuclear waste management field has approached scenario development according to the published literature.

4.1 Why scenarios are made?

As we explained in section 2.2, the safety case is an important document that provides the arguments for the long-term safety of a nuclear waste disposal facility. An integral part of this argument is the safety assessment, which includes scenarios to manage the uncertainties related to the facility. The purpose of the safety assessment is to quantify the possible radionuclide releases and human (or other living organism) exposure to radionuclides during the assessed period.

In the international context, nuclear waste management has been considered to be a politically very sensitive topic. Nuclear waste management programs have been progressing slowly in many countries (see, e.g., national plans of EU member states for radioactive waste and spent fuel management (EC 2021)), mainly due to delays linked to political decision-making. This is partly a consequence of the poor public reputation of nuclear energy, which has further worsened due to major nuclear accidents in recent decades—Chernobyl in 1986 and Fukushima in 2011. There are certainly ethical aspects involved in the discussion about nuclear waste management and nuclear energy in general. This creates a special character on the topic and complicates decision-making.

Geological disposal of nuclear waste implies long time scales, as the activity of many types of nuclear waste remains high for long periods of time, up to a thousand or even hundreds of thousands of years. In short, time scales are geological. After the sealing of the geological disposal facility, its safety will depend on the laws of nature. This means that long-term safety does not depend on human control and possible corrective measures (however, there will probably be a short period, maybe a few hundred years, of institutional control, see e.g. IAEA (2012)). This emphasises the importance of rigorous analysis of possible evolutions of the disposal facility. This in turn emphasises the importance of a transparent, traceable and well-documented scenario development process.

Although there are reservations in legislation (e.g. Government, 1999, 2008) for the possible reversibility of a decision (and also for waste retrieval), licensing-related decisions will rely on safety assessments done before emplacement of waste in the disposal facility. Due to the long time periods that must be covered, the safety assessment of the disposal facility will be mostly based of mathematical modelling. Experimental studies will be too short-term to be used as the only basis. Notwithstanding, experimental studies provide much indispensable input data for mathematical modelling. A specific challenge in experiments and modelling is to cover all possible conditions that the nuclear waste disposal system can be exposed to, e.g. during possible future glaciation. Another challenge stems from the strong couplings between different thermal, hydrological, chemical and mechanical processes inside the system, which by definition may interact with each other directly and indirectly.

Guidelines by the Finnish authority (e.g. STUK 2018) do not provide specific recommendations or approvals on scenario methods or modelling tools that should be used in safety assessment. All nuclear waste producers will have to test and verify/validate the modelling tools they use in the licence application and report the test results to the authority in the safety case. Normally, after having received the licence application, the authority will do independent analyses by itself or have them done by independent expert groups as a reference to the licence applicant's analyses. As the burden of proof lies with the licence applicant, the guidelines by the authority (e.g. STUK 2018, STUK 2018b) only gives general guidelines concerning what things need to be included in the analysis but does not provide detailed instructions about how—or with which tools—to do the safety assessment. The broad guidelines apply to scenario requirements as well. Scenarios are one method of uncertainty management in the safety case. From a safety case point of view, those scenarios, or chains of events, that may result in radionuclide release to the human environment are most relevant.

Summary of why scenarios are needed:

- Nuclear waste management is a safety-critical and sensitive topic that contains great uncertainties.
- Time scales concerning geological disposal are extremely long, up to hundreds of thousands of years.
- After closing, a nuclear waste repository is an autonomous system operating by the laws of nature. Therefore, a safety assessment and preparative measures need to be done in advance.
- The authority requires a safety assessment and scenarios as a part of it, but there are no explicit instructions or approved methods on how they should be done.

4.2 What should scenarios contain?

Answering the question—*What should nuclear waste repository scenarios contain?*—requires elaboration on many aspects: what general phenomenon scenarios need to address, what is actually known about the repository system, and what requirements the competent authority has.

A nuclear waste disposal facility is an extremely multidisciplinary system. This starts already from the waste itself, as spent nuclear fuel covers most of the chemical elements of the periodic table of elements, if not all. Many different disciplines will be needed in the planning of the system. For instance, material research will have to cover a range of engineered materials, but also natural materials. Concerning natural sciences, physics and chemistry will have to be complemented with special scientific fields, such as geology, hydrology, biology and radiochemistry. In the decision-making process, expertise in social sciences and organisation sciences will be needed, and perhaps philosophy and ethics as well.

The multidisciplinary nature of the nuclear waste disposal facility, together with the number of different materials, makes the system coupled in many ways. This means that there are direct and indirect ways the materials and processes can interact with each other, with a wide range of time constants. In addition, couplings between subsystems are often asymmetric, for instance, thermal processes affect hydrologic processes more strongly than vice versa. It calls for coupled experiments and coupled modelling to be able to understand the coupled interactions. In practice, the consequence of coupling is that the effect of a technical optimisation in one subsystem (e.g. a change in material or material volume) is difficult to assess in advance, but the full effect can often be seen after at least a partial long-term safety assessment.

In principle, every disposal facility will be individual because the disposal concept needs to be tailored to the unique geological environment. Before constructing the disposal facility, the geological environment will have to be studied extensively. The sampling points will be limited, however, as one cannot drill the location full of holes. Thus, the geological and hydrological model of the site will be based on a limited number of data points. This state of affairs will cause a specific epistemic-aleatory uncertainty vis-á-vis the understanding of the site.

When considering scenarios for a nuclear waste disposal facility, one must keep certain basic things in mind. First, the purpose of scenarios is to contribute to the safety assessment. Therefore, the primary goal of analysis is to explore the possibility of radionuclides spreading from the disposal facility to the human environment. Figure 9 shows a conceptual framework for scenarios vis-á-vis the spreading of radionuclides. (It is based on a similar multibarrier concept shown in Figure 1.) The figure indicates that radionuclide spreading can be initiated by factors that are external or internal to the system. Internal factors can be related to quality deficiencies in the engineered barrier system and/or internal interactions between coupled thermo-hydro-chemical-mechanical-biological and radiation-related processes (THCMBR processes). Biological processes cover microbial activity. In the nuclear waste field, the factors initiating release are usually called features, events and processes (FEPs).

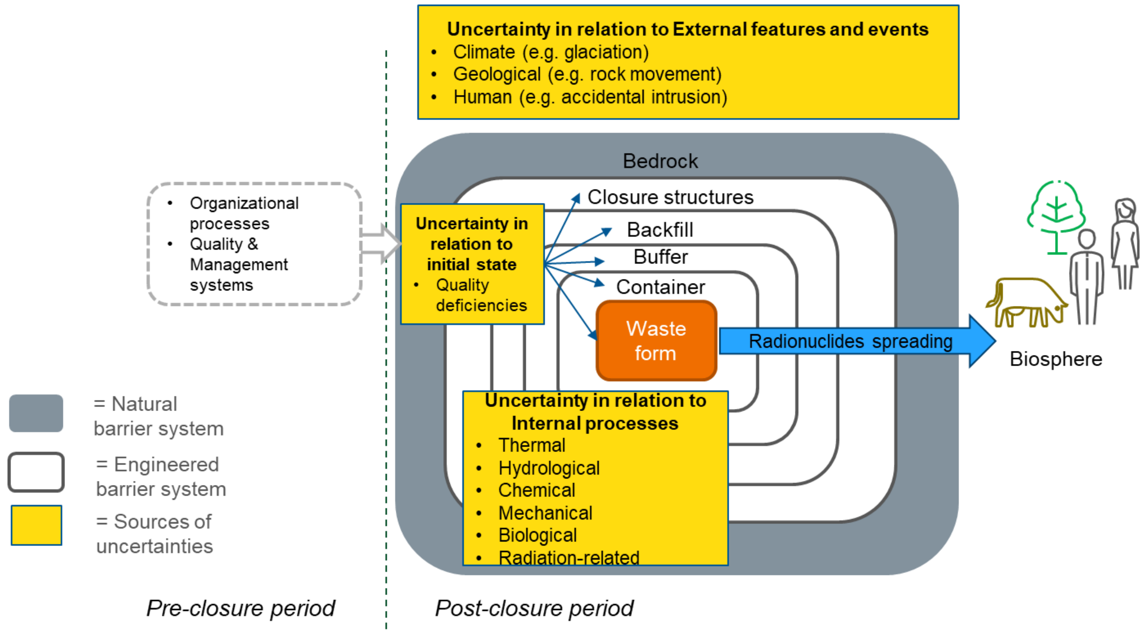

Figure 9. Release of radionuclides through the multibarrier system towards the human environment, the biosphere. Blue indicates that the release takes place via groundwater discharging to the biosphere. Yellow indicates different sources of uncertainties that must be taken into account in scenarios for a safety case.

Figure 9, the dotted line marks the closure time of the disposal facility. Note that while radionuclide spreading can take place only after the closure, pre-closure organisational processes, e.g. quality and management systems, can affect the post-closure evolution of the disposal facility. This is possible since pre-closure activities directly affect the quality of the engineered barrier system and thus the initial state of the disposal facility at the time of closure. Reducing different uncertainties requires different approaches in the sense that analysing organisational factors belong to social science research while analysing the other two belong mostly to technical and natural science research. The two scientific domains have different traditions, which must be taken into account when formulating scenarios.

A reasonable starting point for formulating scenarios that represent plausible futures of the disposal facility system is to focus on what is known about the system. In this respect, the release barrier system is a relevant factor because every disposal facility has a specific design of consecutive release barriers. In addition, for every release barrier, there are various defined safety functions, which describe how the release barrier in question is expected to contribute to long-term safety. For example, for the KBS-3 concept (Figure 1), SKB and Posiva have defined the safety functions shown in Table 3. Each safety function is linked to detailed performance targets and technical design requirements. Discussing these in detail is beyond the scope of this report.

Table 3. Safety functions related to subsystems in the KBS-3 concept (Posiva & SKB, 2017). Buffer refers to 'bentonite' in Figure 1.

Release barrier	**Safety function**
Canister	SF1 Withstand corrosion SF2 Withstand mechanical loads SF3 Maintain sub-criticality
Buffer	SF4 Limit advective mass transfer SF5 Limit microbial activity SF6 Filter colloids SF7 Protect the canister from detrimental mechanical loads – rock shear load SF8 Protect the canister from detrimental loads – pressure load SF9 Resist transformation SF10 Keep canister in position SF11 Retain sufficient mass over the life cycle
Backfill and plug up deposition tunnels	SF12 Keep the buffer in place SF13 Limit advective mass transfer
Closure structures	SF14 Reduce the risk of unintentional intrusion SF15 Avoid the formation of new preferential flow paths SF16 Keep the deposition tunnel backfill in place
Host rock and underground openings	SF17 Isolation from the surface environment SF18 Favourable thermal conditions SF19 Mechanically stable conditions SF20 Chemically favourable conditions SF21 Favourable hydrogeological conditions with limited transport of solutes

Authority requirements

From the licence applicant's perspective, of absolute necessity in scenario analysis are the specific requirements set by the competent authority. In the Finnish case, the Radiation and Nuclear Safety Authority (STUK) gives guidance on the disposal of nuclear waste (STUK 2018). The content of the safety case is described in Annex A of this document. First, scenarios are mentioned in the general description of the purpose of the safety case: "-- *compliance with the requirements concerning long-term radiation safety, and the suitability of the disposal method and disposal site, shall be proven through a safety case that must analyse both* ***expected evolution scenarios*** *and* ***unlikely events impairing long-term safety***." (STUK 2018, p. 19, highlighting added).

Two out of the twelve items guide the content and construction of scenarios. Item A04 gives guidance about the content of scenarios, and item A05 defines three types of scenarios. In addition to these items, scenarios are mentioned twice in connection with the overall safety assessment process. According to the instruction (item 06), the analysis of radiological impacts should be based on conceptual models of the system's safety functions and the release and mitigation processes of radionuclides—and eventually mathematical simplifications of these conceptual models. These models and the input data that is used in the analysis "*shall be* *consistent with the scenario, assessment period and disposal system*" (item A07). In item A10, it is said that it is also possible to use "*complementary considerations, such as calculations by simplified methods, comparisons with natural analogues, or observations of the geological history of the disposal site"* if *"a scenario cannot be comprehensively and reasonably assessed by means of quantitative safety analyses."* According to item A10, "*the significance of such considerations grows as the assessment period increases, and safety evaluations extending beyond the time horizon of one million years can mainly be based on complementary considerations*."

From these rather fragmented items, it is possible to compose some expectations that that authority imposes on scenario analysis. The first observation is that the scope of analysis is divided into "expected evolution" and something else that stems from "unlikely events". This division introduces the concept of *probability* or *likelihood* in the analysis because there is a future that is "expected" to happen. However, the text uses the plural form when talking about the expected evolution scenarios. This implies that there can be several futures that are in the range of expectations and that scenario analysis should cover these. About the content of scenarios, the document gives the following instruction:

> *"**A04.** The scenarios shall be systematically composed to cover any events and factors that may be of relevance to long-term safety and that may arise from:*
> a. *external factors, such as climate changes, geological processes and events or human actions;*
> b. *radiological, mechanical, thermal, hydrological, chemical, biological and radiation-related factors internal to the disposal system;*
> c. *quality non-conformances in the barriers; and*
> *the combined effects of all the aforementioned factors*." (STUK 2018, p. 19).

The above instruction conceptualises scenarios from the system perspective, as scenarios are presented as combinations of factors that are external (point a) and internal (points b and c) to the system. For the question—how should scenarios be composed?—the document gives very little guidance. As can be seen in the quote above, the only instruction is that scenarios "shall be systematically composed". However, there is a clear implication of the overall scenario analysis process in the document. Scenarios are needed for assessing long-term safety and the "suitability" of the proposed disposal concept—as well as the location—for the purpose. This assessment should be carried out using models of the system, and the *models and input data should be consistent with scenarios*. This implies that scenarios need to be descriptions of the "expected evolution" of the system (i.e. possible combinations of different factors affecting the system over time). Based on these descriptions, one should be able to produce input data for impact assessment modelling as well as to evaluate the consistency of the models with these expected evolutions.

In addition to the expected evolutions, there should be more scenarios that represent some "unlikely" events. The different scenario types to be included in the safety case are defined in the instructions as follows:

> **"*A05. The base scenario*** *shall assume that the performance targets defined for each safety function are met. The influence of declined performance of one or several safety functions shall be analysed by means of* ***variant scenarios****.* ***Disturbance scenarios*** *shall be constructed for the analysis of unlikely events impairing long-term safety referred to in para. 316. The argumentation for the assumed extent of the declined performance of a safety function shall be presented.*" (STUK 2018, p. 19, highlighting added).

The definition of disturbance scenario makes a direct reference to unlikely events, so it is reasonable to assume that the other two scenario types are meant to refer to the other goal of scenario analysis, i.e. analysing the expected evolution of the system. This means that, by definition, in the range of expected evolutions of the disposal system, there is one in which the performance targets of each safety function are met and an (unknown) number of alternatives in which the performance of one or several safety functions have declined. The challenge imposed on the licence applicant in scenario development is to create an adequate number of these scenarios to prove the long-term safety of the nuclear waste repository.

Scenario content can be discussed in terms of the system (the factors that scenarios should include) and time. The question of time is covered implicitly in the guideline document (STUK 2018). As was described above, the guidance accepts that scenarios and a numeric safety assessment may not be "comprehensive", and they can be supported by "complementary considerations", especially when the assessment period is very long. In this context, the document states that time horizons going beyond a *million years* are most likely necessary to cover with complementary considerations instead of scenarios. This statement implies that scenario analysis should be a reasonable approach for the safety assessment of the repository system, at least for the first million years after the closure.

Summary of what scenarios should contain:

- The purpose of scenarios is to contribute to the safety assessment. The radiological impact of the nuclear waste repository is caused by the possible spreading of radionuclides to the biosphere. Therefore, the primary goal of scenario analysis is to explore the possibility of radionuclides spreading from the disposal facility to the human environment.
- A nuclear waste repository is a complex system, requiring the analysis of coupled phenomena and implementing multidisciplinary knowledge. The multibarrier system design and the safety functions are the known aspects of the disposal facility, which can be taken as a starting point in scenario development.
- The license applicant needs to follow the requirements of the competent authority in constructing scenarios, but the authority provides practically no instructions on how to make scenarios. The only instruction is that scenarios "shall be systematically composed". In addition, the instruction involves conceptions that demand approaches covering both *probability/likelihood* and *exploration* in the analysis. According to the instructions, scenarios should include factors that are both internal and external to the nuclear waste repository system.

4.3 How does the nuclear waste community approach scenarios?

Scenario approaches and methodologies in connection with nuclear waste disposal projects have been discussed, compared and reported for at least 30 years. Despite some differences in detail, most projects have adopted broadly similar approaches (and ended up with rather similar sets of scenarios to analyse).

The most relevant international expert organisations in the nuclear field are the International Atomic Energy Agency (IAEA), Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD NEA) and Western European Nuclear Regulators' Association (WENRA). OECD NEA develops co-operation between nuclear industries, while the other two are organisations for the regulatory parties. These organisations have worked for decades to define a defendable "prototype" for safety case, see e.g. IAEA (2012), NEA (2012), WENRA (2014). This collaboration also includes scenarios as a central component of the safety case (in particular, the safety assessment, as was shown in Figure 3), and international considerations have served as models when individual national projects have developed their own safety cases.

Different general approaches related to scenarios have been discussed, e.g. the top-down or bottom-up approaches (e.g. IAEA 2012). Top-down scenario approaches start from the defined safety functions, that is, from how individual release barriers are supposed to operate. Because of their central role, safety functions have also been studied separately (e.g. Posiva & SKB 2017). Bottom-up approaches start from considerations on what could happen to the disposal facility. This leads to analysing features, events and processes (FEPs). Various organisations (e.g. NEA 2019) have developed international databases of FEPs, from which individual projects can develop their own subsets.

International expert group reports do not usually discuss the scenario methodology in detail. They do not provide any instructions or proposals on how scenarios have been, or should, be identified and formulated. Therefore, we need to turn to academic studies in this field.

Tosoni et al. (2018) have reviewed the scenario approaches of 14 safety cases in 9 countries reported between 1993 and 2012. Their main focus was on the comprehensiveness of the set of scenarios selected for safety assessment. By comprehensiveness, they mean that all FEPs that significantly influence the system are identified. This is a more defined set of FEPs than what is needed for the description of the complete disposal system. The writers refer to the latter using the concept of completeness. The central findings of the review were (1) one must clarify why scenarios have focused on a limited set of FEPs, (2) there is not a consensus on the interpretation of comprehensiveness that could guide scenario formulation work, and (3) there is a need to analyse epistemic uncertainties in more detail.

Tosoni et al. (ibid.) divided the scenario approaches of safety cases into pluralistic and probabilistic ones. In pluralistic approaches, there are a relatively limited number of scenarios that reflect different assumptions by experts. In probabilistic approaches, scenarios are generated as subsets from a large random sample of futures. Of the safety cases reviewed, ten were classified into pluralistic and four into probabilistic approaches. Probabilistic approaches have lost popularity in the 1990s. The authors emphasize the role of the system model in scenario development. They also discuss the comprehensiveness of the FEP list, which subsequently affects the comprehensiveness of the developed scenarios because the identification of FEPs is the first step in scenario development. They consider comprehensiveness to be a more meaningful (and obtainable) goal in scenario analysis than completeness.

Summary of scenario approaches:

- International expert organisations have studied safety cases and scenario analysis as one part of it. For instance, top-down and bottom-up approaches have been identified as scenario approaches.
- There is no international consensus about the interpretation of comprehensiveness that could guide scenario formulation work.

5 Discussion - Analysis of the safety case as a scenario problem

This chapter summarises the discussion in previous chapters and analyses nuclear waste repository scenarios as a scenario problem. We analyse nuclear waste repository scenarios using the epistemic scenario framework that we developed in Chapter 3 and relate the needs and requirements of nuclear waste repository scenarios (as presented in Chapter 4) to the scenario types that we identified in the literature. The two dimensions of the epistemic framework guide us in thinking about the contents of scenarios in relation to the characteristics of a nuclear waste repository system and the purpose of scenarios in the decision-making context. The latter aspect is necessary for evaluating whether there is a need for a normative or explorative approach to scenario creation.

As explained in Chapter 2, scenarios are an essential part of the long-term safety assessment of the nuclear waste repository. After the disposal of nuclear waste in the repository, it is closed. The purpose of the repository system is to contain and retard dangerous nuclear waste for so long that it is not harmful anymore. The period after the closure is the main concern of the safety assessment. In this period, we can conceptualise the repository system as an autonomous system because its ability to fulfil its purpose is dependent on the performance of the multibarrier system and affected by the laws of nature rather than on human control or corrective measures. To analyse the performance of the repository system, there are two aspects that one knows about the system: (1) the multibarrier system that is designed and constructed for delaying and limiting the spreading of radionuclides from the repository, and (2) the safety functions defined for all main components in the multibarrier system.

In the field of nuclear waste management, mathematical modelling of long-term safety has been developed systematically for at least forty years. As discussed in Section 2.2, this work has resulted in the development of the safety case as a well-established tool for estimating the radiological impact of a nuclear waste repository. Scenario analysis is one important component in the safety case, which is expected to cover the uncertainties in relation to evolving futures. From this perspective, it is evident that the main emphasis of scenario creation is in the system. Scenario analysis is expected to give insight into such questions as: "What might happen in the system in the forthcoming centuries?", "Which (internal) processes or (external) disturbances might affect the system's performance with regard to long-term safety?", "What are the consequences for long-term safety if something unfavourable happens and the system does not function as planned?", "In which conditions might the system not fulfil the requirement of 'being safe'?"

How do the previous questions relate to the scenario approaches that we identified and described in Chapter 3? The first observation is that the emphasis is on the system—what might happen in or to the system, and how the system possibly affects its environment. The second observation is that these questions—and their connection to the overall purpose of safety assessment—interweave normative and explorative elements. On the one hand, one needs to show that the system is (and will be) safe; and in order to do that, one should be able to anticipate all possible/plausible developments and causes that might threaten it. These epistemic aspects make the nuclear waste repository scenarios similar to those approaches that we called *scenario analysis* and *safety analysis* and presented in sections 3.3.1 and 3.3.2. Characteristic of these scenario approaches is that it is not easy to separate the normative and explorative aspects from each other. Normative aims can be achieved through explorative analysis, and explorative purposes may be enforced using normative comparisons between scenarios in terms of some assessment variables.

If we compare nuclear waste repository scenarios to the normative scenario analyses, e.g. the Life-cycle Assessment (LCA), we can find an important difference. In LCA studies, the primary goal of assessment is to find an optimal scenario that minimizes the harmful consequences. In the safety assessment of a nuclear waste repository, the normative aspect stems from the requirement to show that the proposed repository is safe. In this connection, "safe" means that the releasing radionuclides discharging into the biosphere cause estimated dose rates (Sv/a) and release rates (Bq/a) that fall below the safety criteria defined by the nuclear safety authority (in Finland STUK). In principle, only a safe nuclear waste repository is possible because, by definition, a disposal facility failing to comply with safety criteria will not be licenced. This aspect highlights the importance of the safety assessment in decision-making.

Thus, we can formulate a task for the safety assessment of nuclear waste repository: A safety assessment including its scenarios has to demonstrate that the designed repository is safe. This means that a licence applicant needs to analyse and assess the safety of the system in advance (before the government grants the licence and before the repository closes). This aspect emphasizes the explorative nature of repository scenarios because there should be full confidence in the coverage or comprehensiveness of the assessment. For scenarios, this means that all important or all possible and essential internal processes and external factors (disturbances) are taken into account in scenario development.

The process of scenario analysis can be simplified into three steps: (1) Development of scenarios; (2) Quantification of scenarios for the impact assessment; and (3) Impact assessment using a suitable method or model. The difference between the normative and explorative variants is in how they emphasise the different steps of the process. For the normative approaches, such as LCA studies, scenarios are something that can be constructed using “informed expertise” in the selection of “proper parameters” for the analysis. An understanding of the system under consideration—for example, knowledge of which processes produce emissions and which factors affect these processes—guides the selection of the scenario parameters. This selection appears less problematic than the assessment method, which is needed for the third step. In LCA studies, this may mean a discussion on how the system boundary should be defined (i.e. what is included in the system and what is left outside) or how the emissions should be allocated between the different parts of the system.

For the explorative variant of scenario analysis, the emphasis between scenario development and impact assessment is different. Scenario development is in a key role in the realisation of the explorative aspect of the analysis. Imagination, open-mindedness but also rigour and systematic precision can support the explorative aspiration of analysis, which is the aspiration to include all possible factors causing uncertainties or unknown consequences in the system or its environment. However, this does not mean that the assessment step would not require great effort or be a straightforward task without some tricky decisions. For example, developing a system dynamic model requires great effort and involves similar decisions about system boundaries as in LCA models, while using a general energy system modelling approach requires effort in localizing the model to represent the local conditions. This is actually a kind of paradox in the explorative scenario analysis. On the one hand, one needs to separate scenario development from the impact assessment in order to ensure the explorative aspect of analysis. On the other hand, it is not possible to separate the scenario analysis from the assessment step because it is needed for getting the “result” or outcome from the analysis.

The intermediary step between scenario development and impact assessment—the quantification of scenarios—is not without significance, even if it often appears as just a mechanical “selection of parameter values”. It is important to remember that the scenario analysis process produces information *only* on those alternatives and those conditions that are included in the analysis throughout the process. In every step, something is left out that was there in the previous step, and this reduces the amount of knowledge that is produced. All factors that are left out from the scenario development limit the range of possible futures and influencing mechanisms that can be covered. All scenarios that are left out of the quantification—and all ranges that are left out in quantification—limit the range of possible futures that are studied. Finally, all aspects of the system that are left outside the model boundary limit the amount of knowledge that is produced. In conclusion, scenario analysis produces knowledge on only those aspects that are included in the analysis in all steps. Yet, all these “limitations” need to be made in order to carry out the analysis till the end and produce the results from the scenario analysis. Therefore, it becomes essential to separate all the steps from each other and document all choices and decisions transparently.

Table 4 shows a proposal for an analysis scheme that can be used for developing a scenario analysis approach for nuclear waste repository scenarios. It contains questions that are intended for designing or evaluating the scenario process.

An essential starting point in scenario analysis is to know the system that is studied, what kind of phenomena or processes there are that affect the operation of the system, and what kind of impacts these have on each other and on the whole system. For the repository system scenarios, the safety functions of the multibarrier system are a starting point for this analysis. As explained above, the complexity of the system and the wide range of disciplinary knowledge required in this analysis create challenges for this task. Therefore, this phase requires methodological approaches that support collaboration between subject-matter experts and allow the analysis of possible chains of events to identify critical factors and the analysis of the cross-impacts of these factors. For this purpose, well-tested methodological models can be found from the field of safety analysis (e.g. event trees, cross-impact assessment). After a thorough analysis of the influencing factors and their importance, combinations of these factors should be made. In quantitative approaches, this is a mathematical operation that produces a large number of combinations. One challenge is to develop methods for selecting an adequate number of scenarios so that the goals of safety assessment are achieved.

Table 4. Decomposition of the nuclear waste repository scenario analysis.

Scenario analysis process	**(1) Development of scenarios**	**(2) Quantification of scenarios for impact assessment**	**(3) Impact assessment modelling**
Expected evolutions *(Baseline and variant scenarios)*	Which factors may decrease the performance of safety functions? How are these factors and their impacts interconnected? Which are the most significant factors to be included in scenarios? Which are consistent combinations of the included factors? Which combinations cover the evolution of the system "adequately"?	Which scenarios are included in the assessment? How are these scenarios quantified for the assessment? Do the selected scenarios and quantifications cover the range of expected evolution "adequately"?	Are the models and input data consistent with scenarios? What does the impact modelling tell about the expected evolution of the system and its impacts? What does the analysis results not tell? (What was excluded in the preceding steps?) How reliable is the result? What are the sources of unreliability? Is there a need for improvement in any step of the analysis?
Disturbance scenarios	Which "unlikely events" may impair the performance of the repository system? What is the mechanism causing decreasing performance?	Which events should be included in the assessment? How can the mechanisms be quantified?	What are the consequences of the events? How reliable is the result? What are the sources of unreliability? Is there a need for improvement in any step of the analysis?

The challenges in relation to modelling and especially questions concerning its reliability and possible sources of error are beyond this report's scope. However, we want to make some general remarks about this topic. The disposal facility can be considered as an autonomous system because its safety is essentially based on the laws of nature, not on human control or corrective measures. The laws of nature also control the phenomena that take place in the system and affect its evolution. *Laws of nature*, as used here, means the set of interlinked fundamental groups of mathematical equations that are used to model the evolution of the system. The equations will remain the same for the period to be studied. Any disturbances affecting the system can be treated in modelling as changing parameter values and/or boundary conditions of the set of equation groups.

Considering external FEPs as factors disturbing the evolution of the disposal facility, it may be useful to see that no matter when the disturbance occurs, its effect is to shift the state of the disposal facility to a new position, either instantaneously or by starting a gradual process. After the disturbance, the laws of nature will start acting on the system. The final state of the system will depend on the initial state, the possible disturbance(s) and the time the laws of nature act on the system. The quantitative difference between Scenario A and Scenario B concerning the final state of the system is defined by how the scenarios are parametrised and how the impact assessment is done in practice.

By definition, disturbance scenarios are expected to analyse unlikely events impairing the long-term safety of a nuclear waste repository. Therefore, these scenarios can be seen as being similar to what Börjeson et al. (2006) defined as what-if scenarios. These scenarios investigate what will happen in some specific conditions. In the case of a nuclear waste repository, the task would be to investigate whether radionuclide release is possible if some "unlikely event" takes place. The analysis task for this type of scenario is to find out all possible "unlikely events" that might impair the performance of the repository system and how this impairment happens. Some of the "unlikely events" that need to be analysed are mentioned in the guideline (STUK 2018, paragraph 316). But for a complete analysis, it might be necessary to enhance the explorative element and use methods that promote brainstorming or other idea-generating approaches. In this kind of ideation, the combination of expertise and a wider range of background knowledge may produce better results than being limited to a very homogenous pool of expertise. Understanding the mechanism of influence is very important because it has an effect on how the assessment step should be carried out. It is necessary to understand whether the effect is a short-term disturbance or a trigger for a slower long-term change and how wide the affected zone in the system is. All these issues have an effect on the modelling and parametrisation of the scenarios.

Our analysis of the nuclear waste repository scenarios concludes that this task requires systematic approaches that involve normative and explorative elements. Similar approaches were found in the literature review in alternatives we call scenario analysis and safety analysis. These approaches combine scenarios and model-based impact assessment. They utilise systematic, mathematical methods in scenario development, but brainstorming or other types of idea generation or workshop approaches may be essential for improving the explorative aspect of analysis. It is characteristic of systematic scenario development methods that in the analysis of complex systems, the number of scenarios becomes large. Therefore, the selection of scenarios for the impact assessment step becomes a crucial question. The scope of produced knowledge decreases in every step of the process, but this is an unavoidable issue in the scenario analysis. The challenge is to find an acceptable balance between the scope of the analysis and an efficient use of resources (human resources, funding available, time).

It is characteristic of scenario studies that the process design and selection of methodological approaches need to be done every time for the specific application case. Even the formal scenario methods always require the implementation of expert processes, and process designs may require a compromise due to resource availability or other external reasons. The nuclear waste repository creates a challenging task for scenario analysis due to its safety-critical character and the long time-frame required for the analysis. Also, the multidisciplinary character of phenomena present in the system brings extra complexity to the analysis. Therefore, it is evident that the scenario method for a nuclear waste repository should be some kind of hybrid, combining aspects from different scenario approaches. This hybrid method should be developed by combining methodological expertise with the subject-matter expertise of the nuclear waste community.

We wish that the epistemic scenario framework could also contribute to the methodological development. We developed the framework in order to be able to combine and compare different scenario approaches that appeared in different disciplinary fields. However, it is important to note that we do not propose the framework to be a classification tool that would identify some "pure" types or classes of scenarios. Instead, we wish that it could be useful for evaluating the scenario problem at hand, and this evaluation would guide the identification of relevant scenario approaches. The epistemic approach promotes thinking of the limitations and strengths of different approaches in knowledge creation. Another possible use would be for evaluating scenario processes from the knowledge creation perspective. Success in knowledge creation is always a wider question than just making the right choices in the selection of methodologies. In addition to that, it covers issues related to the organisation of the process where these methods are applied as well as questions about how outcomes are communicated and used in decision-making.

Figure 10 shows how the epistemic scenario framework could serve the evaluative purpose in the field of nuclear waste management. As the knowledge that is created by scenario analysis is connected to the safety assessment of the nuclear waste repository, it is important to emphasize the normative element of such analysis. In this context, the central questions are to ensure that the analysis is adequate for the purpose, but also that its results are understandable for those who need the information. The selected method and rigour in its application can have a role in the first aspect, but the latter one is something that concerns questions of communication and how well the results are explained and evaluated. One outcome of our analysis was that the normative aspect of scenario analysis is often interwoven with explorative aspects, and therefore the process and selected methods and implementation processes are central in ensuring the explorative outcome.

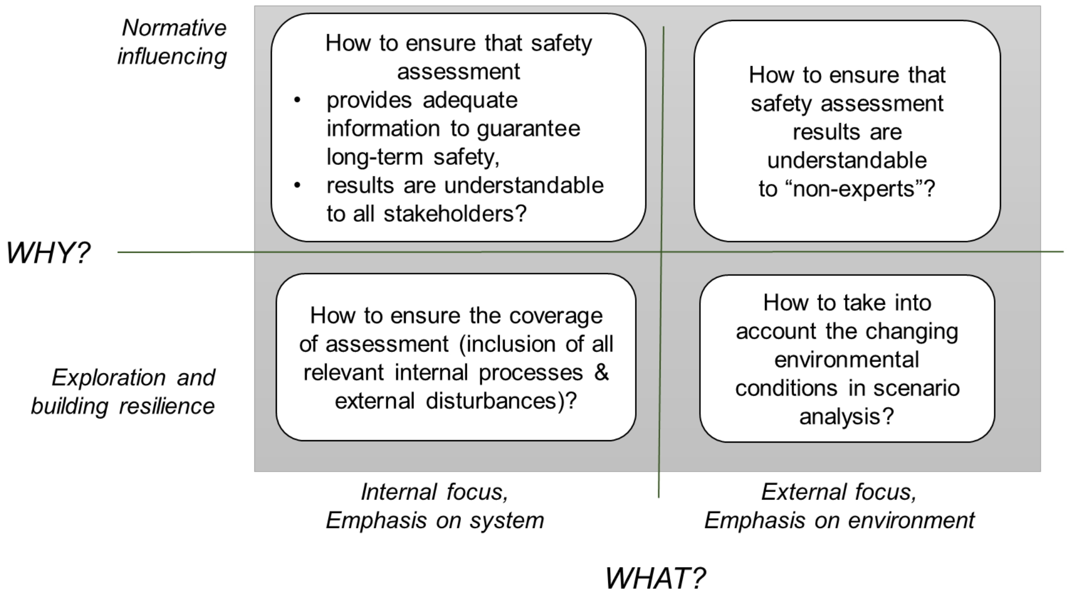

Figure 10. Using the epistemic framework for evaluative purposes.

This study was able to provide only a limited approach to the scenario method and its role in nuclear waste management. In the following, we discuss a few limitations of this study and possible questions for further research.

1) The integrative literature approach adopted in this study did not allow for comparative analyses in relation to the scenario method. Such questions as temporal changes in the application of various scenario approaches in one field or quantitative comparisons of the prevalence of different scenario approaches across different fields are beyond the scope of the selected qualitative approach. For these types of questions, a quantitative bibliometric analysis would be a better methodological choice. On the other hand, the epistemic approach of this study was limited to the rather practical level of combining knowledge purposes and methods of knowledge production. Especially in the context of nuclear waste management, there would be space for more extended epistemological and ethical considerations. An example of such questions is how scenario knowledge involves the inter-generational aspects inherent in nuclear waste management.
2) Another limitation of this study, and a possible topic for further research, is to widen the practitioner's perspective. This study was based only on written sources, and the review of scenario approaches of the nuclear community relied mainly on documents produced by international organisations and authorities. Closer contact with the nuclear waste management community (by including interview data in the analysis, for example) or a more extended and directed literature search would increase the understanding of possible constraints and challenges related to scenario studies in the nuclear waste management field. One interesting aspect in relation to this topic might be a temporal analysis of how the scenario approach in the nuclear waste field evolved. For example, Finnish decision-making on nuclear waste management is done in phases, and every phase should produce an improved version of the safety case. This also indicates that the database and role of scenarios should evolve with successively updated safety cases. With this in mind, it is noteworthy that according to Tosoni et al. (2018), many recent international safety cases have ended up in relatively similar scenarios based on a limited set of FEPs. A question for further research would be, 'What practices and conditions in the field produce such an outcome?'
3) A third possible point of departure for further research would be to bridge the gap between theory and practice in relation to scenario-making. This study increased the preparedness for an integrative approach from a theoretical perspective, but for complete integration of theory and practice, a different research design would be necessary. As scenario-making is integrally connected to the application context, one possibility would be to apply the principles of action research. Action research is a social scientific research approach that aspires to developmental goals with a simultaneous action process (e.g. in a participant organisation) and research linked together by critical reflection. This kind of research design would enable better integration with the practitioners who keep safety in their focus in their daily practice and possibly find improved ways to provide practical support for managerial decision-making and utilisation of the ideas stemming from a theoretical view on scenarios.

References

Alizadeh, R., & Soltanisehat, L. (2020). Stay competitive in 2035: a scenario-based method to foresight in the design and manufacturing industry. Foresight, 22(3), 309–330. https://doi.org/10.1108/FS-06-2019-0048

Awopone, A. K., Zobaa, A. F., & Banuenumah, W. (2017). Techno-economic and environmental analysis of power generation expansion plan of ghana. *Energy Policy, 104*, 13-22. doi:10.1016/j.enpol.2017.01.034

Aziz, A., Ahmed, S., Khan, F.I. (2019). An ontology-based methodology for hazard identification and causation analysis. Process Safety and Environmental Protection, 123, pp. 87-98. Barker, K. E., Cox, D., & Sveinsdottir, T. (2011). Foresight on the future of public research metrology in Europe. Foresight, 13(1), 5–18. https://doi.org/10.1108/14636681111109660

Baldissone, G., Fissore, D., Demichela, M. (2016). Catalytic after-treatment of lean VOC-air streams: Process intensification vs. plant reliability, Process Safety and Environmental Protection, 100, pp. 208-219.

Bishop, P., Hines, A., & Collins, T. (2007). The current state of scenario development: an overview of techniques. Foresight

Bowman, G. (2016). The practice of scenario planning: an analysis of inter-and intra-organizational strategizing. *British Journal of Management*, *27*(1), 77-96.

Bradfield, R., Wright, G., Burt, G., Cairns, G., & Van Der Heijden, K. (2005). The origins and evolution of scenario techniques in long range business planning. Futures, 37(8), 795–812.

Bubbico, R., Greco, V., Menale, C. (2018). Hazardous scenarios identification for Li-ion secondary batteries. Safety Science, 108, pp. 72-88.

Börjeson, L., Höjer, M., Dreborg, K. H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. Futures, 38(7), 723–739.

Cameron, I., Mannan, S., Németh, E., Park, S., Pasman, H., Rogers, W., Seligmann, B. (2017). Process hazard analysis, hazard identification and scenario definition: Are the conventional tools sufficient, or should and can we do much better? Process Safety and Environmental Protection, 110, pp. 53-70.Crawford, M. M. (2019). A comprehensive scenario intervention typology. Technological Forecasting and Social Change, 149(September), 119748.

Das, A., Halder, A., Mazumder, R., Saini, V. K., Parikh, J., & Parikh, K. S. (2018). Bangladesh power supply scenarios on renewables and electricity import. *Energy (Oxford), 155*, 651-667. doi:10.1016/j.energy.2018.04.169

Ducot, G., & Lubben, G. J. (1980). A typology for scenarios. Futures, 12(1), 51–57.

Durbach, I. N., & Stewart, T. J. (2012). Modeling uncertainty in multi-criteria decision analysis. *European journal of operational research*, *223*(1), 1-14.

EC, 2021, National programmes, European Commission 26.2.2021, (https://ec.europa.eu/energy/topics/nuclear-energy/radioactive-waste-and-spent-fuel/national-programmes-management-spent-fuel-and-radioactive-waste_en).

Folhes, R. T., Aguiar, A. P. D. de, Stoll, E., Dalla-Nora, E. L., Araújo, R., Coelho, A., & Canto, O. do. (2015). Multi-scale participatory scenario methods and territorial planning in the Brazilian Amazon. Futures, 73, 86–99. https://doi.org/10.1016/j.futures.2015.08.005

Godet, M. (2000). The art of scenarios and strategic planning: tools and pitfalls. *Technological forecasting and social change*, *65*(1), 3-22.

Government, 1999, Government Decision (478/1999) on the safety of disposal of nuclear waste http://www.finlex.fi/fi/laki/alkup/1999/19990478, VnP 478/199 (in Finnish).

Government, 2008, Government Decree (736/2008) on the safety of disposal of nuclear waste https://finlex.fi/en/laki/kaannokset/2008/en20080736.pdf, VNA 736/2008.

Guo, Y., Zhu, W., Yang, Y., & Cheng, H. (2019). Carbon reduction potential based on life cycle assessment of China's aluminium industry-a perspective at the province level. *Journal of Cleaner Production, 239*, 118004. doi:10.1016/j.jclepro.2019.118004

Haimes, Y.Y., Kaplan, S., Lambert, J.H. (2002). Risk filtering, ranking, and management framework using hierarchical holographic modelling. Risk Analysis, 22 (2), pp. 383-397.

Heugens, P. P. M. A. R., & Van Oosterhout, J. (2001). To boldly go where no man has gone before: Integrating cognitive and physical features in scenario studies. Futures, 33(10), 861–872.

IAEA, 2012.The Safety Case and Safety Assessment for the Disposal of Radioactive Waste. Specific Safety Guide. IAEA Safety Standards Series No. SSG-23. (https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1553_web.pdf).

Jain, P., Rogers, W.J., Pasman, H.J., Mannan, M.S. (2018). A resilience-based integrated process systems hazard analysis (RIPSHA) approach: Part II management system layer. Process Safety and Environmental Protection, 118, pp. 115-124.

Kaufmann, S., & Lohaus, M. (2018). Ever closer or lost at sea? Scenarios for the future of transatlantic relations. Futures, 97, 18–25. https://doi.org/10.1016/j.futures.2017.04.007

Kotir, J. H., Smith, C., Brown, G., Marshall, N., & Johnstone, R. (2016). A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta river basin, Ghana. *The Science of the Total Environment, 573*, 444-457. doi:10.1016/j.scitotenv.2016.08.081

Kuzmina, K., Prendeville, S., Walker, D., & Charnley, F. (2019). Future scenarios for fast-moving consumer goods in a circular economy. Futures, 107, 74–88. https://doi.org/10.1016/j.futures.2018.12.001

Lettner, M., Schöggl, J., & Stern, T. (2017). Factors influencing the market diffusion of bio-based plastics: Results of four comparative scenario analyses. *Journal of Cleaner Production, 157*, 289-298. doi:10.1016/j.jclepro.2017.04.077

Levesque, A., Pietzcker, R. C., Baumstark, L., De Stercke, S., Grübler, A., & Luderer, G. (2018). How much energy will buildings consume in 2100? A global perspective within a scenario framework. *Energy (Oxford), 148*, 514-527. doi:10.1016/j.energy.2018.01.139

Lin, B., & Wang, X. (2014). Promoting energy conservation in China's iron & steel sector. *Energy (Oxford), 73*, 465-474. doi:10.1016/j.energy.2014.06.036

Luo, M., Song, X., Hu, S., & Chen, D. (2019). Towards the sustainable development of waste household appliance recovery systems in china: An agent-based modeling approach. Journal of Cleaner Production, 220, 431-444. doi:10.1016/j.jclepro.2019.02.128

Luukkanen, J., Akgün, O., Kaivo-oja, J., Korkeakoski, M., Pasanen, T., Panula-Ontto, J., & Vehmas, J. (2015). Long-run energy scenarios for Cambodia and Laos: Building an integrated techno-economic and environmental modelling framework for scenario analyses. *Energy (Oxford), 91*, 866-881. doi:10.1016/j.energy.2015.08.091

McDowall, W. (2014). Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. Futures, 63, 1–14. https://doi.org/10.1016/j.futures.2014.07.004

Merrie, A., Keys, P., Metian, M., & Österblom, H. (2018). Radical ocean futures-scenario development using science fiction prototyping. Futures, 95, 22–32. https://doi.org/10.1016/j.futures.2017.09.005

Moonis, M., Wilday, A.J., Wardman, M.J. (2010). Semi-quantitative risk assessment of commercial scale supply chain of hydrogen fuel and implications for industry and society, Process Safety and Environmental Protection, 88 (2), pp. 97-108.

Mustonen, S. M. (2010). Rural energy survey and scenario analysis of village energy consumption: A case study in the Lao People's Democratic Republic. *Energy Policy, 38*(2), 1040-1048. doi:10.1016/j.enpol.2009.10.056

NEA 2019, International Features, Events, and Processes (IFEP) List for the Deep Geological Disposal of Radioactive waste, Version 3.0, OECD NEA Radioactive Waste Management Committee, 165 p.

NEA, 2012. Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste. Outcomes of the NEA MeSA Initiative. ISBN 978-92-64-99190-3.(http://www.oecd-nea.org/rwm/reports/2012/nea6923-MESA-initiative.pdf).

Nielsen, S. K., & Karlsson, K. (2007). Energy scenarios: a review of methods, uses and suggestions for improvement. International Journal of Global Energy Issues, 27(3), 302-322.

Oedewald, P., Pietikäinen, E. and Reiman, T. (2011). 3. A guidebook for evaluating organizations in the nuclear industry – an example of safety culture evaluation. Swedish Radiation Safety Authority, Research Report 2011:20.

Paltrinieri, N., Khan, F., Amyotte, P., Cozzani, V. (2014). Dynamic approach to risk management: Application to the Hoeganaes metal dust accidents, Process Safety and Environmental Protection, 92 (6), pp. 669-679.

Paltrinieri, N., Wilday, J., Wardman, M., Cozzani, V. (2014). Surface installations intended for Carbon Capture and Sequestration: Atypical accident scenarios and their identification. Process Safety and Environmental Protection, 92 (1), pp. 93-107.

Panos, E., & Kannan, R. (2016). The role of domestic biomass in electricity, heat and grid balancing markets in Switzerland. *Energy (Oxford), 112*, 1120-1138. doi:10.1016/j.energy.2016.06.107

Posiva & SKB, 2017.Safety functions, performance targets and technical design criteria for a KBS 3V repository. Conclusions and recommendations from a joint SKB and Posiva working group. Posiva SKB Report 01, 116.

Poteri, A. 2013, Simplifying solute transport modelling of the geological multi-barrier disposal system. VTT Science: 42, VTT, Espoo, 2013, 63 p. + app. 141 p. ISBN 978-951-38-8097-2 (Softback ed.), 978-951-38-8098-9 (PDF) http://www.vtt.fi/inf/pdf/science/2013/S42.pdf

Raele, R., Boaventura, J. M. G., Fischmann, A. A., & Sarturi, G. (2014). Scenarios for the second generation ethanol in Brazil. Technological Forecasting and Social Change, 87, 205–223. https://doi.org/10.1016/j.techfore.2013.12.010

Ramírez, R., Österman, R., & Grönquist, D. (2013). Scenarios and early warnings as dynamic capabilities to frame managerial attention. Technological Forecasting and Social Change, 80(4), 825–838. https://doi.org/10.1016/j.techfore.2012.10.029

Rasilainen, K., Gharbieh, H., Olin, M. & Ylönen M. 2019, Safety case methodology for nuclear waste disposal - possible update considerations for Finnish usage, VTT Technology 364, 36 p. + app. 1 p., https://www.vtt.fi/inf/pdf/technology/2019/T364.pdf

Rasilainen, K., Gharbieh, H., Olin, M. & Ylönen M. 2019, Safety case methodology for nuclear waste disposal - possible update considerations for Finnish usage, VTT Technology 364, 36 p. + app. 1 p., https://www.vtt.fi/inf/pdf/technology/2019/T364.pdf

Reiman, T. and Oedewald, P. (2009). Evaluating safety critical organizations. Focus on the nuclear industry. Swedish Radiation Safety Authority, Research Report 2009:12.

Roubelat, F. (2006). Scenarios to challenge strategic paradigms: Lessons from 2025. Futures, 38(5), 519–527. https://doi.org/10.1016/j.futures.2005.09.001

Saswattecha, K., Kroeze, C., Jawjit, W., & Hein, L. (2017). Improving environmental sustainability of Thai palm oil production in 2050. *Journal of Cleaner Production, 147*, 572-588. doi:10.1016/j.jclepro.2017.01.137

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. Journal of Business Research, 104, 333-339.

Soetanto, R., Dainty, A. R. J., Goodier, C. I., & Austin, S. A. (2011). Unravelling the complexity of collective mental models: A method for developing and analysing scenarios in multi-organisational contexts. Futures, 43(8), 890–907. https://doi.org/10.1016/j.futures.2011.06.013

Soria-Lara, J. A., & Banister, D. (2018). Collaborative backcasting for transport policy scenario building. Futures, 95. https://doi.org/10.1016/j.futures.2017.09.003

STUK, 2018. Guide YVL D.5. Disposal of nuclear waste, 39 p. + app 4, (https://www.stuklex.fi/en/ohje/YVLD-5).

STUK, 2018b, Radiation and Nuclear Safety Authority Regulation on the Safety of Disposal of Nuclear Waste, REGULATION STUK Y/4/2018, https://www.stuklex.fi/en/maarays/stuk-y-4-2018.

Talberg, A., Thomas, S., & Wiseman, J. (2018). A scenario process to inform Australian geoengineering policy. Futures, 101, 67–79. https://doi.org/10.1016/j.futures.2018.06.003

TEM, 2019, Nuclear Energy Act, https://www.finlex.fi/en/laki/kaannokset/1987/en19870990.pdf

Torraco, R. J. (2005). Writing integrative literature reviews: Guidelines and examples. Human resource development review, 4(3), 356-367.

Tosoni, E., Salo, A. & Zio, E. 2018. Scenario Analysis for the Safety Assessment of Nuclear Waste Repositories: A Critical Review. Risk Analysis, Vol. 38, No. 4, pp. 755-776 (DOI: 10.1111/risa.12889)

Tourki, Y., Keisler, J., & Linkov, I. (2013). Scenario analysis: a review of methods and applications for engineering and environmental systems. Environment Systems & Decisions, 33(1), 3-20.

Trost, T., Sterner, M., & Bruckner, T. (2017). Impact of electric vehicles and synthetic gaseous fuels on final energy consumption and carbon dioxide emissions in Germany based on long-term vehicle fleet modelling. *Energy (Oxford), 141*, 1215-1225. doi:10.1016/j.energy.2017.10.006

Turunen, J., Pohjola, J. & Lipping, T. 2018, Sensitivity analysis of radionuclide transport in biosphere analysis. STUK-A261. Salomaa, S, Lusa, M. & Vaaramaa, K. (eds.). Cores Symposium on Radiation in the Environment - Scientific Achievements and Challenges for the Society, 16-17.4.2018, Helsinki, Finland. http://urn.fi/URN:ISBN:978-952-309-425-3

Ulusçu, Ö.S., Özbaş, B., Altiok, T., Or, I. (2009). Risk analysis of the vessel traffic in the strait of Istanbul. Risk Analysis, 29 (10), pp. 1454-1472.

van Notten, P. W. F., Rotmans, J., van Asselt, M. B. A., & Rothman, D. S. (2003). An updated scenario typology. Futures, 35(5), 423–443.

Varho, V., & Tapio, P. (2013). Combining the qualitative and quantitative with the Q2 scenario technique - The case of transport and climate. Technological Forecasting and Social Change, 80(4), 611–630. https://doi.org/10.1016/j.techfore.2012.09.004

Vignes, A., Muñoz, F., Bouillard, J., Dufaud, O., Perrin, L., Laurent, A., Thomas, D. (2012). Risk assessment of the ignitability and explosivity of aluminum nanopowders. Process Safety and Environmental Protection, 90 (4), pp. 304-310.

Volkery, A., & Ribeiro, T. (2009). Scenario planning in public policy: Understanding use, impacts and the role of institutional context factors. Technological Forecasting & Social Change, 76(9), 1198-1207. https://doi.org/10.1016/j.techfore.2009.07.009

WENRA, 2014, Report Radioactive Waste Disposal Facilities Safety Reference Levels - 22 December 2014, Western European Nuclear Regulators' Association (WENRA), Working Group on Waste and Decommissioning (WGWD) http://www.wenra.org/media/filer_public/2015/03/18/srl_disposal_final_version_2014_12_22.pdf

Wilday, J., Paltrinieri, N., Farret, R., Hebrard, J., Breedveld, L. (2011b). Addressing emerging risks using carbon capture and storage as an example. Process Safety and Environmental Protection, 89 (6), pp. 463-471.

Wilday, J., Wardman, M., Johnson, M., Haines, M. (2011a). Hazards from carbon dioxide capture, transport and storage. Process Safety and Environmental Protection, 89 (6), pp. 482-491.

Wilkinson, A., & Eidinow, E. (2008). Evolving practices in environmental scenarios: A new scenario typology. Environmental Research Letters, 3(4).

Wilkinson, A., Kupers, R., & Mangalagiu, D. (2013). How plausibility-based scenario practices are grappling with complexity to appreciate and address 21st century challenges. Technological Forecasting and Social Change, 80(4), 699–710.

Williams, B. (2020) Hierarchical holographic modelling and the theory of scenario structuring, Available at https://www.briangwilliams.us/global-catastrophic-risks/hierarchical-holographic-modelling-and-the-theory-of-scenario-structuring.html

Winkler, J., & Moser, R. (2016). Coping with strategic uncertainty: framework development and scenario derivation for a JV decision in the Russian truck industry. Foresight, 18(4), 357–378. https://doi.org/10.1108/FS-01-2016-0002

Wright, D., Stahl, B., & Hatzakis, T. (2020). Policy scenarios as an instrument for policymakers. Technological Forecasting & Social Change, 154, 119972. https://doi.org/10.1016/j.techfore.2020.119972

Xin, P., Khan, F., Ahmed, S. (2017). Dynamic hazard identification and scenario mapping using Bayesian network. Process Safety and Environmental Protection, 105, pp. 143-155.

Yokokawa, N., Kikuchi-Uehara, E., Sugiyama, H., & Hirao, M. (2018). Framework for analyzing the effects of packaging on food loss reduction by considering consumer behavior. *Journal of Cleaner Production, 174*, 26-34. doi:10.1016/j.jclepro.2017.10.242

Zahraei, S. M., Kurniawan, J. H., & Cheah, L. (2019). A foresight study on urban mobility: Singapore in 2040. Foresight, 22(1), 37–52. https://doi.org/10.1108/FS-05-2019-0044

Zegras, C., & Rayle, L. (2012). Testing the rhetoric: An approach to assess scenario planning's role as a catalyst for urban policy integration. Futures, 44(4), 303–318. https://doi.org/10.1016/j.futures.2011.10.013

Zhu, C., Fan, R., & Lin, J. (2020). The impact of renewable portfolio standard on retail electricity market: A system dynamics model of tripartite evolutionary game. *Energy Policy, 136*, 111072. doi:10.1016/j.enpol.2019.111072