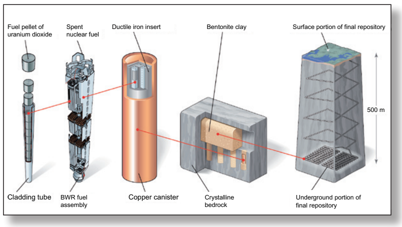
Nuclear Development
2013

The Economics of the Back End of the Nuclear Fuel Cycle



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Nuclear Development

The Economics of the Back End of the Nuclear Fuel Cycle

NEA No. 7061

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Cover photo: The Swedish/Finnish KBS-3 method for final disposal of spent nuclear fuel (Swedish Nuclear Fuel and Waste Management Company – SKB)

Foreword

Spent nuclear fuel and high-level waste from the fuel cycle of commercial nuclear power plants represent a small proportion of the radioactive waste produced globally by different industries, but they account for the greatest radioactivity content and longevity. Yet while technologies are well developed and widely employed for the treatment and disposal of the much larger volumes of less radioactive low-level and short-lived intermediate-level waste, no final disposal facilities have yet been fully implemented for spent nuclear fuel and high-level waste. A lack of experience in the complete deployment of deep geological repositories, combined with the extensive periods required for the implementation of back-end solutions, have thus contributed to growing uncertainties about the costs associated with managing spent nuclear fuel and high-level waste. The issue has become a central challenge for the nuclear industry and a matter of continued concern and debate for the public.

Many useful reports have been produced over the years, describing national waste management approaches or making suggestions on how to analyse disposal costs. Of particular note is the extensive work being carried out by the NEA Radioactive Waste Management Committee and its working parties. In recent years, a number of studies have also been undertaken in NEA member countries, examining the costs of the disposal of spent fuel and high-level waste. However, these national studies are linked to specific policy choices, practices and regulations, with the outcomes varying significantly across countries and thus not directly comparable.

Since no comprehensive overview of the overall state of knowledge on the costs of back-end solutions across NEA countries has been made available recently, this study was included in the programme of work of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle. The goal was to develop a more in-depth understanding of economic issues and methodologies for the management of spent nuclear fuel and high-level waste from commercial power reactors.

Using official data supplied by national authorities, this report offers a review of general principles and frameworks, as well as available and prospective back-end options, appraising current policies and practices in different countries and focusing on the costs of the various solutions adopted. Estimates of the final costs are generally used to define and verify the status of the financial provisions required to meet such costs. Mechanisms adopted by countries for the accrual and control of these provisions, fund features and management approaches are also considered in the report, together with additional measures set out in some national systems to protect against residual risks.

A quantitative analysis of economic factors is performed in the second part of the report, encompassing a comparative appraisal of existing economic models. Through a simple static model, high-level cost estimates are calculated for idealised systems and scenarios rather than analysing specific country approaches. These cost estimates cover direct disposal of spent nuclear fuel, partial recycling in light water reactors and multiple plutonium recycling in a symbiotic configuration of light water and fast reactors. Calculations are performed for different discount rates to determine major cost drivers and, through sensitivity analyses, to highlight the impacts of variations in key economic parameters. For these calculations, essential input data on the capital, operation and maintenance costs of different back-end facilities was provided by member countries.

The main outputs include the total levelised fuel cycle cost and its composition, with a particular focus on the back-end components.

In addition to economic considerations, the basis for any informed socio-political decisions in this area has to be broadened to a comprehensive evaluation of qualitative factors such as security of energy supply, non-proliferation, public attitudes and environmental effects, all of which are discussed in this report.

Acknowledgements

This study was carried out under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle and prepared by an ad hoc expert group (see list in Appendix 7) under the chairmanship of Hans Forsström. The participation of expert group members is gratefully acknowledged. Special thanks are due to Hans Riotte for his consultant support in the preparation of Chapter 4, David Shropshire for his consultant input in the comparative appraisal of existing economic models in Chapter 3, and Hans Forsström for his attentive and continual review of the report during its preparation.

Maria Elena Urso and Alexey Lokhov, from the NEA Secretariat, also contributed to the study as scientific secretaries, with support from Ron Cameron, Head of the NEA Nuclear Development Division. The model used for the high-level cost estimates presented in Chapter 3 was developed and applied by Alexey Lokhov.

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Executive summary

Objectives of the study on the economics of spent nuclear fuel management

Of all civil radioactive waste generated by various industries (including medicine, agriculture and research), the largest portion comes from nuclear power generation and related fuel cycle processes. Only a small part of this is high-level waste (HLW), consisting by and large of packaged spent nuclear fuel (SNF) or HLW from reprocessing.

The feasibility and costs of SNF management and consequent disposal of the ultimate waste continue to be the subject of public debate in many countries, with particular concerns often being raised about the slow progress in implementing final disposal for civilian HLW.

In some cases, very large estimates are given for future waste management and disposal costs, ranging up to many tens of billions of dollars. In a few instances, these high estimates have a large component for the costs of clean-up and waste disposal from military nuclear facilities, although they are often quoted without this caveat. Claims have been made at times that costs for SNF/HLW management are completely unknown and that, consequently, there is no accurate way to establish the size of funds or assess their adequacy.

Several studies on SNF/HLW management costs have been carried out in individual countries, but they inevitably reflect national policy choices and practices, and hence their results are not directly comparable with those of other countries. In addition, many useful reports have been produced, describing national waste management approaches or making suggestions on how to analyse disposal costs. Of particular note is the extensive effort being undertaken by the Radioactive Waste Management Committee (RWMC) of the OECD Nuclear Energy Agency (NEA). Since 1975 the RWMC has provided a platform for international co-operation in the management of radwaste from nuclear installations (including long-term waste management and facility decommissioning) – a neutral forum for policy makers, regulators and implementing organisations to discuss state of the art and emerging issues, and develop solutions that meet the diverse needs of its participants. Through its wide-ranging programme of work the committee helps to establish a common ground for national regulatory frameworks, to share and advance best practice (e.g. by supporting international peer reviews) and to contribute to progress on scientific and technical knowledge (e.g. through joint projects and specialist meetings). Current subjects addressed by the RWMC span among disposal issues, including safety case preparation and licensing of geological repositories, decommissioning and societal confidence. Comprehensive country reports and/or country profiles have been compiled and are regularly revised and made available online.

These materials have formed a broad base of reference for the present study, which, nevertheless, takes a different but complementary approach to that of the RWMC. It provides:

- A review of the cost estimations undertaken in NEA member countries, together with an assessment of processes for the establishment and management of funds.
- A high-level assessment of the costs of the full cycle and its components, in the case of three idealised strategies (current and potential) for managing the back

end. This assessment includes a sensitivity analysis, which helps to identify the principal cost drivers for the economics of the back end.

The report does not analyse or reproduce the details of the costing approach used in individual countries or their project management process, nor does it make judgments on the appropriateness of costs derived within a specific national context. Moreover, given the distinctive features and needs of specific national programmes, the results of the cost assessment cannot simply be transposed to individual countries without a more detailed and adapted cost analysis. The analysis presented here aims to assist policy makers in OECD/NEA member countries who have specific responsibilities for making strategic choices about back-end options and for ensuring the adequacy of the funding.

In 2011, the OECD/NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) established the Ad hoc Expert Group on the Economics of the Back End of the Nuclear Fuel Cycle to conduct the study and mandated it with the following specific objectives:

- To understand economic issues and methodologies for the management of SNF in NEA countries, including the funding mechanisms in place or under consideration, how the funds are managed and the extent of any unfunded liabilities.
- To assess the available knowledge from different countries on the costs of the various options for the long-term management and final disposal of radioactive waste, and, to the extent possible, compare the cost estimates of different countries on a common basis.
- To evaluate, in particular, the impact of uncertainties, e.g. variations in cost estimates for SNF interim storage, reprocessing, encapsulation, and final disposal.

It has been noted that considerable volumes of legacy waste have been accumulated in some countries from earlier activities, primarily of a military nature. While it is recognised that legacy waste clean-up may entail substantial costs, this study does not attempt to address the issue, since the information obtained was insufficient to make a comprehensive analysis.

Conclusions from the study are given in the boxes outlined in each section, while recommendations are brought together at the end of this summary.

Current status and progress of national policies and programmes

All the waste deriving from the SNF management must be managed safely and in a manner that protects humans and the environment, taking into account a broad and complex range of issues, sometimes interrelated: science and technology, safety and environmental protection, non-proliferation and safeguards, economics and finance, and ethical and societal aspects.

In addition to HLW, short-lived and long-lived low- and intermediate-level radioactive waste is generated at all stages of the fuel cycle.[1] In countries with a sizeable fleet of nuclear power plants (NPPs), considerable experience is available on waste and materials processing, conditioning, storage, transport and disposal of low- and intermediate-level waste (LILW). In many countries all steps have been implemented on a commercial scale for their management. However, in some cases there are still issues related to special types of radioactive waste (e.g. mixed waste and graphite) that require further consideration. Technological developments remain to be achieved in the future, but they are not expected to strongly influence LILW management options.

1. For the back end, long-lived low- and intermediate-level radioactive waste is derived almost exclusively from reprocessing.

Industrially available options for SNF management

For the long-term management of SNF, two major options have been adopted commercially to date:

- Direct disposal, where the fuel is used once and is then regarded as waste to be disposed of.
- Partial recycling, where the spent fuel is reprocessed to recover unused uranium and plutonium for recycling in light water reactors, in the form of reprocessed uranium oxide (REPUOX) and mixed-oxide (MOX) fuel, respectively. Irradiated MOX and REPUOX bundles can be either stored (with the perspective of their reprocessing and recycling in future fast reactors – FRs) or disposed of after encapsulation.

Advanced systems and fuel cycle concepts for the longer-term future have been studied theoretically or on a pilot scale, principally with the dual objective of reducing the mass and radioactivity of waste destined to final disposal and optimising the use of natural resources. However, the deployment of fast neutron systems and associated advanced fuel cycles (FCs) will still require increased investment and the development of new infrastructures for advanced systems and processes, as well as significant adaptation efforts, including in legal and regulatory frameworks. The first commercial Generation IV systems[2] are not likely to be available before the 2030s, and they are not expected to become a major part of installed nuclear capacity until well after 2050.

A number of countries with major nuclear programmes operate or have plans to develop reprocessing and fuel fabrication facilities, and some have the capacity to also provide these services to other countries (currently, however, only France and the Russian Federation offer continued services to other countries). Some 10% of reactors worldwide have been licensed to use MOX, and uranium recycling is being carried out by a few reactor operators on a limited scale. With the significant experience accrued to date, plutonium and uranium extraction (PUREX), reprocessing and MOX recycling can be regarded as mature technologies. Continuous advancements in the PUREX process have led to a decrease of solid waste volumes, effluents and consequential environmental impacts, while MOX fuel performance has matched the performance record of uranium oxide (UOX) fuel.

Regardless of the specific strategy adopted, the final disposal of HLW or SNF (treated as HLW in the once-through fuel cycle) is the ultimate stage of the fuel cycle. There is general agreement that deep geological repositories (DGRs) offer the best solution in this regard. The development of advanced fuel cycles (including those which use accelerator driven systems) could also significantly reduce the amounts of SNF and HLW to be disposed of. However, the need to manage residual actinides (from losses) and fission products (FP) will remain since the process is not completely efficient. There will still, therefore, be a need for disposal facilities, although they could be smaller and/or fewer in number. Hence, progress towards implementation of DGRs remains a high priority for the future use of nuclear energy.

> Both industrial fuel cycle options, direct disposal or partial recycling, as well as any prospective advanced option, will ultimately require an operational repository for final disposal. The major difference in the deep geological repository needed for the different options will be in relative size.

2. www.gen-4.org/Technology/evolution.htm.

Long-lived solid radioactive waste and SNF have been safely and securely stored in NEA countries for several decades now. In most cases, interim storage facilities were initially designed to operate for periods up to 50 years, but extended intermediate storage is becoming an increasingly adopted practice, and operational periods of 100 years or longer are being considered. This is sometimes due to the long time frames needed for the deployment of final repositories, but can also be considered as a strategic choice. In a few cases, political and societal hurdles have challenged the establishment of a national strategy for spent nuclear fuel, with significant policy shifts over time. Other factors can also influence continued long-term storage, including for example the small volumes of waste accumulated in the country, difficulties with transport or site selection, or inadequacy of available funding. By prolonging spent fuel storage, fuel cycle options are kept open and further study and consideration can be given to alternatives, before reaching a final decision on a national strategy. However, longer-term interim storage gives rise to questions related to the long-term integrity of fuel elements, which is raised as a concern by the public.

Progress in DGR implementation

While there is one operational deep geological repository, the Waste Isolation Pilot Plant (WIPP), in the Delaware Basin of New Mexico, which has been receiving military transuranic radioactive waste for permanent disposal since 1999, no civilian DGR for SNF and HLW from NPPs and their FCs has yet been built in the world. However, national legal and regulatory frameworks and programmes are in place in many countries for the implementation of the necessary steps in SNF/HLW management. Three DGRs are expected to become operational in the next decade so as to provide disposal for SNF (in Finland and Sweden) and HLW and LILW from reprocessing (in France). In other countries, longer time horizons are envisaged, spanning from two to many decades. Countries where the most significant advances in disposal programmes have occurred are generally those with a long-term continuity in policy positions.

Waste Management Organisations (WMOs) have been established in most NEA countries. WMOs are generally separate non-commercial entities that can hold various responsibilities, from the centralised collection of SNF/waste and the related processing capabilities to the final disposal. They can be either state-owned organisations or organisations that are owned by the waste producers. Their responsibilities require a combination of attributes: technical capability, accountability and, ideally, organisational stability and political independence, as well as the ability to negotiate with relevant stakeholders and elicit consent, primarily for DGR siting.

Stakeholder engagement at the different stages of programme implementation is crucial to the success of DGR implementation, and stepwise approaches that foster partnerships with potential host communities are increasingly favoured, resulting, in some countries, in improved public acceptance. Specific studies have also addressed societal issues (at the international level, e.g. various reports by the NEA as detailed in Section 2.3.3, and at the national level, e.g. the 2005 Iribarne's report published in France[3]).

Advances have occurred in national programmes for HLW and SNF disposal. Conditions favouring progress include the maturity of the industry, the long-term continuity in policy positions and a high degree of emphasis on community partnerships in the implementation of strategies.

3. www.ladocumentationfrancaise.fr/var/storage/rapports-publics/054000355/0000.pdf.

Funding and costing

Most countries perform assessments of the costs for SNF/HLW management, encompassing the different stages of the back end (e.g. interim storage, encapsulation, transport). Factors influencing such costs are manifold and often country specific (e.g. different physical and technical conditions, individual national regulations, economic conditions and the different itemisation, boundary conditions and inclusion of costs). Thus, variations of cost estimates obtained in different countries can be quite large, and comparisons between assessments are very difficult.

> Assessments of the costs for managing spent fuel and radioactive waste from the civil fuel cycle are essential to establish the size of liabilities and guarantee their financing. Cost assessments are performed regularly in most countries, encompassing the various stages of the back end. However, differences across individual assessments can be quite large, making direct comparisons very difficult. Variations are attributable to disparate factors including differences in assumptions, technical solutions and national conditions.

Much of the expense for managing SNF and HLW can appear long after electricity and revenue generation has ended. Hence, it is important that future waste management costs are estimated and funds are accrued to adequately cover these costs when they arise. Funding systems have been established in most countries, in line with existing international instruments[4] and agreed principles. The waste producer is generally held responsible for accumulating the funds, in accordance with the "user/polluter pays" principle. The most common mechanism of accrual is through the revenues obtained from electricity generation. The fees and levies are accumulated in internally or externally managed funds.

The established financial arrangements cover most existing liabilities. Nonetheless, there is considerable variability in the level of funds accumulated in different countries, with no harmonised, generally agreed approach to funding arrangements and to developing the cost estimates upon which funding must be based. It should, however, be noted that the estimation of the future cost is only one component in the determination of the funds required. Other important (and not always predictable) factors include the real rate of return of the funds, scheduling of expenditures and the remaining NPP operational lifetime over which fees can be levied.

As the costs for reprocessing and recycling are normally incurred while the reactors are still in operation and can thus be seen as a part of the operational cost, no segregated funds are mandated to cover such costs on a legal basis. However, in practice, operators establish funds dedicated to reprocessing.

> Expenses for disposal will appear over extended periods, with much of the expenditure occurring long after power production and income from electricity generation have ceased. It is important that appropriate financial arrangements are established and that the accrual of adequate and available funds for the eventual implementation of the selected back-end strategy is carefully pursued.

Owing to the long time frames and technical developments required, calculations of back-end costs are subject to significant uncertainties and potential changes. As more accurate knowledge of costs is gained through further progress in the implementation of

4. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, and the Euratom Council Directive 2011/70.

programmes, uncertainties should gradually diminish. To help ensure continued fund sufficiency and to address changes, cost estimates and funding requirements are updated at regular intervals, taking into account new technical knowledge and actual fund developments.

> Cost estimates for future facilities, including repositories, entail many uncertainties, which will only be reduced as experience is gained in implementing the necessary infrastructure.
>
> To verify continued fund sufficiency and to address changes, cost estimates and funding requirements are generally updated at regular intervals, taking into account new technical knowledge and actual fund developments.

Ring-fencing of funds is also required in order to ensure that funds are only used for the intended purpose. Although segregation of funds is generally pursued by most national legislations, this has not always been the case in every country.

Generally, legal requirements also require that funds should be managed in a low-risk manner, for example, by depositing them in the national account, investing them in government bonds or following a financing strategy established by a designated body. Even these "safer" options, however, do not entirely protect against the financial uncertainties and the instabilities of national economies, as experienced in recent times, which exacerbates the challenges faced by countries. Should unfunded financial liabilities arise (e.g. following bankruptcy of the operator and its parent companies), it is always the state that ultimately remains responsible. Sometimes additional measures are taken to provide further safeguards to the state.

> To secure the availability of funds, ring-fencing is required so that resources accrued are only used for the intended purpose. Segregation of funds is pursued by most but not all countries in their national legislations. Some funding systems contain further inbuilt features to minimise risks; for instance, in some countries securities and guarantees may be requested from nuclear operators to protect against unforeseen developments.

Theoretical cost analysis for selected SNF management strategies

One of the primary aims of this study has been to assess the available knowledge from different countries on the costs of the various options for the long-term management of spent nuclear fuel and, to the extent possible, compare the cost estimates of different countries on a common basis. However, owing to major differences and specificities in individual national contexts, a direct cross-country comparison of SNF/HLW management costs was not considered to be feasible in the study. Instead, simulations of generic and theoretical cases for idealised systems were performed based on the cost information provided and through the development and application of a high-level static model. The input data used in the calculations (generally provided by the members of the experts group for their respective countries) were those available at the time when the analysis was performed (end of 2012). However, national cost assessments are subject to continuous reviews and refinements, and since that time some countries have updated (or are revising) their estimates. Although these new estimates were not incorporated, changes in absolute values of some input data are not expected to significantly alter the main outcomes of this analysis, which essentially aims to identify principal cost drivers and not to determine precise absolute values.

The evaluation of the cost for the total fuel cycle (including both the back-end and the front-end components, so that the use of recycled materials and the resulting savings in the requirements of fresh uranium can be taken into account for recycling options), and the breakdown of these costs, as well as a sensitivity analysis of costs associated with the management of spent nuclear fuel from light water reactors (LWRs), were performed for three assumed generic strategies:

- Open or once–through FC, with direct disposal of spent nuclear fuel.
- Partial recycling or twice-through FC, where REPUOX and MOX are recycled once in LWRs and then disposed of.
- Multiple plutonium recycling with LWRs and fast reactors (FRs). This strategy includes single MOX and REPUOX recycling in LWRs and multiple plutonium recycling in FRs.

In addition to parameters defining the system (size of the nuclear fleet, mass flows), the key input data used for the calculations were overnight investment costs and operation and maintenance costs for the various fuel cycle facilities in each strategy (largely based on the country data obtained by means of a questionnaire). All calculations have been performed assuming that all nuclear reactors operate for 60 years, and that all the back-end facilities are constructed exactly at the time when they are required, with no delays.

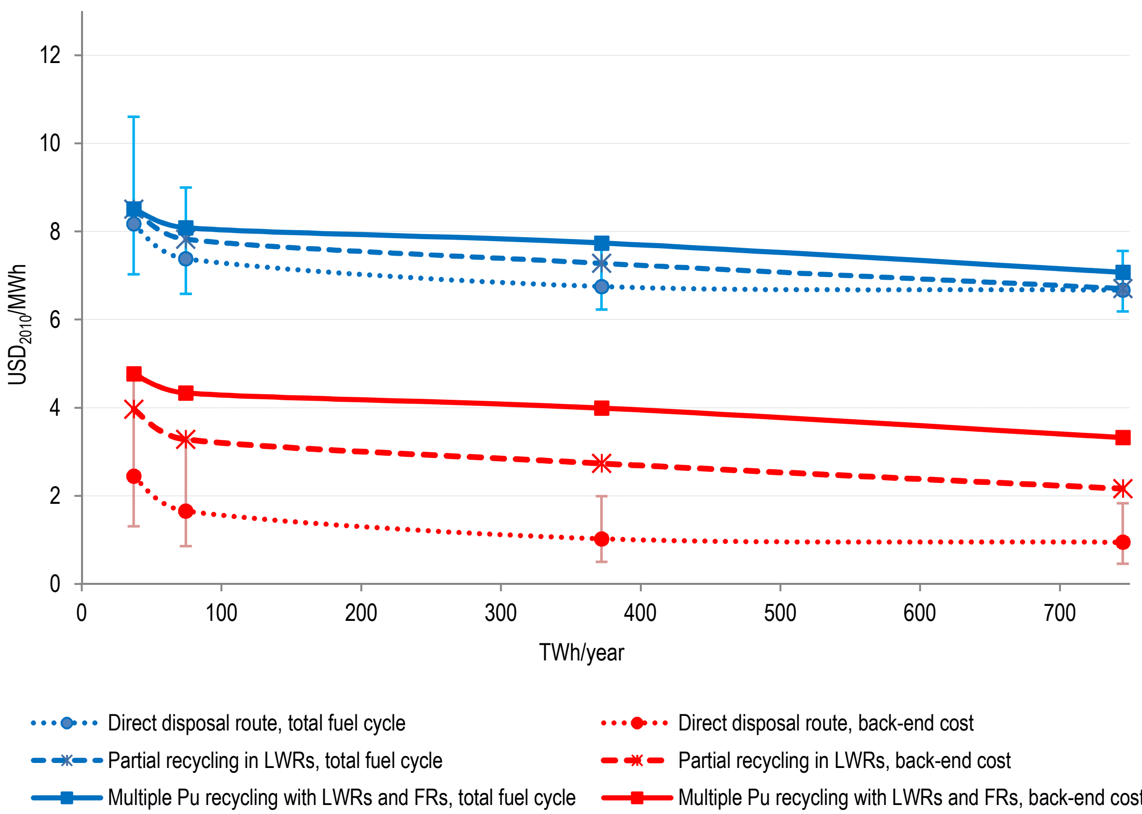
Since low discount rates are more realistic for long-term public benefit projects, the levelised fuel cycle costs were calculated for 0% and 3% real discount rates. The results of the calculation of the levelised cost of the fuel cycle, its detailed breakdown and its sensitivity analysis for the three strategies were performed for different system capacities (from 25 TWh/year to 800 TWh/year – see Figure ES.1). The following general observations can be drawn from the results obtained:

- In all strategies considered, the fuel cycle cost component associated with the management of SNF represents a relatively small fraction of the total levelised costs of electricity generation. For example, the historical cost of electricity generation in France was estimated by the *Cour des Comptes* at about USD 60/MWh. According to the results of this analysis, the total fuel cycle cost then would represent less than 13% and the back-end cost would be about 6.5% of this historical cost. However, even these small fractions could translate into large absolute costs depending on the size of the nuclear programme and the period of electricity generation.
- The total fuel cycle costs calculated are lower for the open fuel cycle option, but differences between the three options considered are relatively small and, for this analysis, within the uncertainty bands. These are influenced by the uncertainties regarding input data and by the assumed discount rate. In the recycling options, additional costs from reprocessing are being offset by the savings on fuel costs at the front end.
- For small systems, fixed costs are more dominant, so costs rise disproportionally as the system size decreases.
- Since the specific costs decrease with the size of the system, there may be economic benefits in sharing different fuel cycle facilities between countries and/or utilities.

The results of the FC cost calculations performed show that costs calculated for the open fuel cycle option are lower than for the other idealised options assessed. Differences among the three options in the total fuel cycle component of the levelised costs of electricity are, however, within the uncertainty bands, given the uncertainties around some input data. For the recycling options, additional costs from reprocessing are being offset by the savings on fuel costs at the front end. Differences are more noticeable if the back-end component of the fuel-cycle cost is considered in isolation, since the offsetting effects are not taken into account.

It is important to note that, for all options assessed, the FC cost component associated with the management of SNF represents a relatively small fraction of the total levelised costs of electricity generation. However, these differences could translate into large absolute costs depending on the size of the nuclear programme and the period of electricity generation.

Figure ES.1: Total fuel cycle and back-end levelised costs for different reactor fleets and strategies, 3% discount rate*



* Uncertainty bands are only plotted for the direct disposal case. Similar bands apply to the other options.

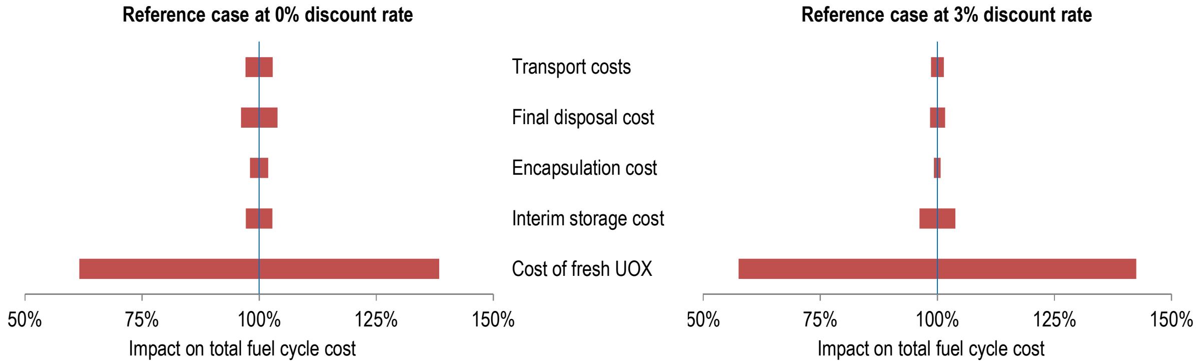
A sensitivity analysis (see Figure ES.2) has been performed in relation to the cost of the fresh UOX fuel, costs of different fuel cycle facilities, the discount rate, the cost premium for fast reactors and the implementation schedule (for the direct disposal strategy):

- Although the uncertainties regarding the future costs for DGR are considerable, in absolute terms, the impact on the total fuel cycle cost is fairly small. As shown in Figure ES.2, a 50% increase in DGR costs (which in absolute terms would be a large sum for larger nuclear programmes) gives rise to an increase in the total fuel cycle costs by a few percentage points.
- In contrast, the total cost of the nuclear fuel cycle strongly depends on the cost of fresh UOX fuel, which in turn depends on the prices of natural uranium, conversion and enrichment services, and fuel fabrication costs. Given uncertainties in the input data, it is difficult to accurately estimate the UOX price which renders one or the other strategy more economical. Advanced recycling options will only be economically advantageous if the price of UOX fuel (and thus the price of natural uranium, enrichment services, etc.) increases significantly from the current values. This would imply an even greater increase in the prices of natural uranium. For example, in the analysis of a system of 400 TWh/year and at a 3% discount rate, the *multiple Pu recycling in LWRs and FRs* would become attractive if the cost of fresh UOX was ~50% higher than those assumed as the reference in the calculation. This corresponds to prices of natural uranium of about USD 270-300/kgU (for unchanged prices of other front-end services such as enrichment), which is more than 100% higher than the reference assumption on the cost of natural uranium defined in this study.
- In both the recycling strategies considered in this study, the second largest sensitivity after the cost of UOX is the cost of reprocessing.
- The fuel cycle cost of the most advanced option, *Multiple Pu recycling with LWRs and FRs*, is also sensitive to the FR cost premium.[5] The results obtained for the reference cost scenario suggest that this advanced option would be more economical than the direct disposal route only if the FR cost premium is low (i.e. if FRs and LWRs have comparable capital and operating costs).
- Overall, the uncertainties related to the full recycling option remain the largest since only sparse data are available for these systems and no commercial system is in current operation.
- A sensitivity analysis with respect to the implementation schedule was performed for the direct disposal of spent nuclear fuel strategy, assuming delays of 20 and 50 years in the construction of the SNF encapsulation facility and DGR. Delays in the implementation of such facilities lead to extended interim storage of the SNF, and thus the escalation of the back-end component of the fuel cycle cost if using a zero discount rate. However, with positive discount rates, delays lead to lower back-end costs. The impact of delays is significantly smaller than the uncertainty band on the back-end costs. This simple analysis does not take into account the possible increased degradation of SNF due to longer interim storage, which would lead to a further increase of undiscounted back-end costs.

5. Fast reactors are expected to be more expensive than LWRs, thus a special cost premium for their construction and operation has been introduced. This extra cost is attributed to the back-end component since, in *Multiple Pu recycling with LWRs and FRs* strategy, the fast reactors are considered as a means for managing the SNF.

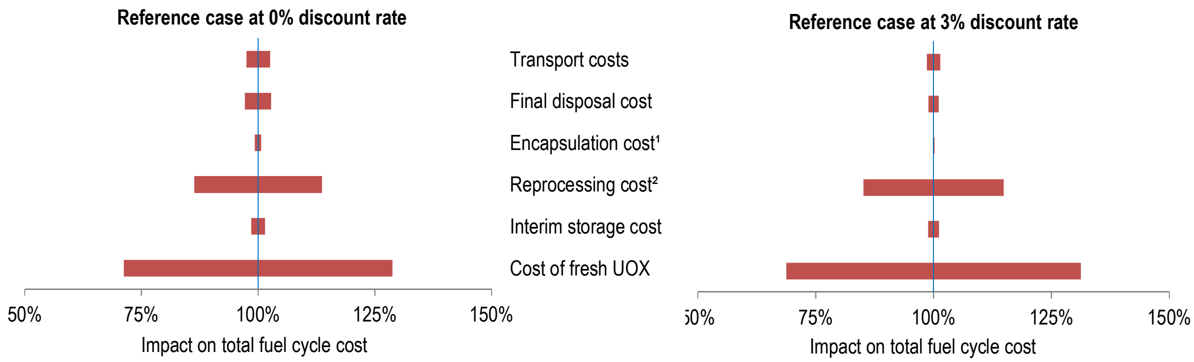
Figure ES.2: Impact on the total fuel cycle cost of ±50% change in costs, for a 400 TWh/year system

Direct disposal route



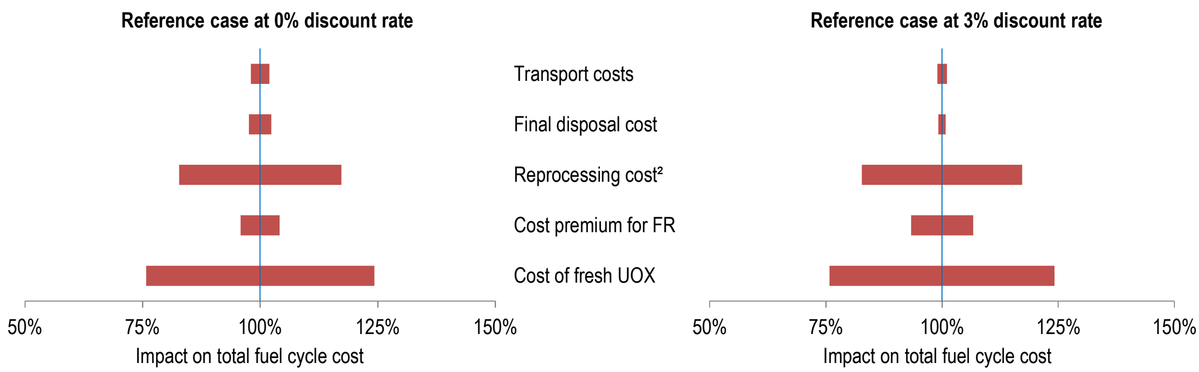
Partial recycling in LWRs

Twice-through (REPUOX and MOX) and disposal of the spent MOX and spent REPUOX



Multiple Pu recycling with LWRs and FRs

MOX and REPUOX recycling once in LWRs and multiple plutonium recycling in FRs



1. Encapsulation of spent MOX and REPUOX.
2. Reprocessing of SNF, MOX fabrication and HLW vitrification.

Sensitivity analyses show that in all three strategies, the total fuel cycle cost is most sensitive to the cost of fresh UOX fuel, which encompasses the price of natural uranium and enrichment services. Other influential factors are:

- interim storage and deep geological repository costs in the direct disposal strategy (though a 50% increase in deep geological repository costs, which in absolute terms would be a large sum for larger nuclear programmes, gives rise to an increase in the total fuel cycle costs by a few percentage points);
- the cost of reprocessing in both recycling strategies;
- the fast reactor cost premium for the multiple plutonium recycling option.

Advanced SNF management options would be economically advantageous only if UOX fuel prices were significantly higher than current values and if FR cost premiums were low.

The assessment conducted in the study is a high-level analysis for idealised systems. Its purpose is to understand the major impacts on back-end costs of the different options and, more specifically, to identify the cost drivers. However, the assessment cannot be simply transposed into a specific national context. This would require a more detailed and adapted cost analysis. In addition, we noted that the cost uncertainties related to the full recycling option are greatest, since this strategy is furthest from commercialisation.

Economics is only one of many factors influencing the decisions regarding SNF management options. It is clear that any evaluation of the comparative merits of the different back-end options will need to be considered in the specific contexts of individual countries and would not be taken purely on economic grounds. A number of qualitative factors may have an important or decisive impact on any decision making regarding back-end options for the nuclear fuel cycle. Some of these factors are discussed in the report. This multi-criteria approach is important in evaluating the relative importance of the various factors in any national context.

Alongside economic considerations, different qualitative factors come into place in the selection of back-end strategies. These encompass:

- political issues, like security of supply and non-proliferation;
- issues of an administrative, governmental infrastructural or social nature, like regulation, safety, public attitudes and transport; along with
- more technical aspects, like environmental protection, retrievability, waste production and future technological developments.

The relative importance of these elements is intricately linked to specific national contexts and may shift over time, so that different factors may outweigh others in different countries and priorities may change with time.

It has been noted that, whatever the determining factors of a national back-end policy are, any significant shift in policy has the potential to induce considerable additional costs, which may even become dominant in the economics of any fuel cycle. This was the case with the added cost of the once-through fuel cycle in the United States, due to the cancellation of the Yucca Mountain project.

Recommendations

The following recommendations from the Ad hoc Expert Group were endorsed by the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) and the Radioactive Waste Mangement Committee (RWMC). The numbering here follows the order used in Chapter 5:

1. While there may be reasons to extend the interim storage of SNF, these should not prevent governments from maintaining vigorous efforts towards the establishment of deep geological repositories, thereby addressing legitimate public expectations and fulfilling the "intergenerational equity" principle.
2. Public involvement in the establishment and implementation of the SNF management strategy is considered vital, and mechanisms to improve stakeholder participation and transparency should be a high priority.
3. Governments should continue to be vigilant in ensuring that the funding systems adopted are stable and robust and that financial resources accrued by waste producers for the management of their waste will be adequate and available at the time they are needed. The following features are considered essential:
   - Regular and frequent reviews to allow for newly accrued knowledge on technical aspects and actual fund developments, as well as other qualitative factors (e.g. sociopolitical), to be taken into account and for emerging shortfalls to be swiftly addressed through the necessary corrective actions.
   - Ring-fencing of funds to ensure that resources are only used for the intended purpose.
4. For countries that are committed to the ongoing use or development of nuclear energy, comparisons of the costs of different strategies for managing the back end should be drawn on the basis of the full fuel cycle cost. For countries that are phasing out or have already exited nuclear power, a direct back-end cost comparison may be more appropriate. In all cases, assessments made for total or partial FC cost comparisons should be transparent about the assumptions made and the scope of the analysis.
5. In any decision-making process regarding the choice of an SNF management strategy, a multi-criteria approach should be adopted at the national level that expands the quantitative economic considerations to include qualitative factors. These can have an important (or even determining) influence in the final decision and may also have a direct impact on the costs.
6. Where issues of long-term fuel supply and reduction of waste volumes are particularly important (e.g. in countries with larger nuclear programmes) R&D on advanced nuclear systems, including FRs, should be supported by governments, since their implementation holds the potential for enhancing the long-term sustainability of nuclear power, notably in relation to management of waste. In this context, further engineering and cost analyses will be important to reduce the uncertainties in the costs of implementing advanced fuel cycle options.
7. International co-operation and sharing of experience for safe, reliable and economic implementation of back-end strategies should continue. Given the significant economic costs and expertise required for their realisation, sharing FC facilities and infrastructure would especially benefit countries with small nuclear programmes.

Chapter 1. Introduction: Management of radioactive waste in NEA member countries

1.1. Background

The feasibility and costs of managing and ultimately disposing of radioactive waste from nuclear facilities continue to be the subject of public debate in many countries, with particular concerns often being raised about a lack of experience in implementing final disposal of spent nuclear fuel (SNF) and high-level waste (HLW) from reprocessing. In some cases, very large estimates are given for future waste management and disposal costs, ranging up to many tens of billions of dollars. The cost estimates are often quoted without clearly specifying what is included. In most cases they cover the management and disposal of spent fuel and waste from commercial power reactors. In a few cases, however, these high estimates also include the costs of clean-up and waste disposal from military nuclear facilities, although they are often quoted without this caveat.

A number of studies have been carried out in OECD Nuclear Energy Agency (NEA) member countries in recent years, examining the costs of disposal of SNF and HLW. In many countries, assessing all future waste management costs is a legal obligation. The cost calculations, however, include various uncertainties, due, for example, to possible delays in implementing programmes and possible changes in the regulatory requirements that will apply. The studies on waste management costs carried out in individual countries inevitably reflect current national policy concerns and practices, and hence tend to produce results that are not directly comparable with those of other countries. Another factor that adds complexity is the state of current knowledge on options for the treatment or conditioning of legacy waste. Furthermore, the planned profile of expenditures on waste management and disposal over time will be important in determining the overall costs and funding requirements.

Estimates of the eventual costs of radioactive waste management and disposal are often used to assess the adequacy of funds that are being set aside to meet these needs. Different countries have put in place varying legal and regulatory arrangements setting out who is responsible for waste management and disposal, and how funds are to be accumulated and managed in the interim period of at least several decades.

Most financial liabilities for long-term waste management and disposal are covered by such arrangements. However, legacy waste remains in some countries (usually from the early days of nuclear development), the management of which is partly or wholly unfunded.

The overall aim of this NEA study is to produce a review across NEA member countries of the costs of management and disposal of SNF and HLW from commercial power reactors and their impact on the fuel cycle costs for different fuel cycles. This is complemented by an economic analysis of three strategies with a view to understanding the differences and, in particular, identifying the principal cost drivers for the economics of the back end.

After defining the general objectives of the study, in order to set the context, this chapter provides a brief introduction, illustrating the classification of radioactive waste and giving a high-level overview of how these are managed in NEA member countries.

1.2. Objectives and approach

The key objectives of this study are the following:

- To review economic issues and methodologies for the management of SNF and HLW in NEA countries and, to a lesser extent, in selected other countries – including the funding mechanisms in place or under consideration, how the funds are managed and the extent of any unfunded liabilities.
- To assess the available knowledge from different countries on the costs of the various options and, to the extent possible, compare the cost estimates of different countries on a common basis.
- To assess the impact on the fuel cycle costs of SNF and HLW management and disposal for different fuel cycles.

To analyse, in particular, the impact of uncertainties, for example:

- variations in cost estimates for SNF reprocessing;
- potential delays in the implementation of the disposal options.

In order to accomplish these objectives, an Ad hoc Expert Group on the Economics of the Back End of the Nuclear Fuel Cycle was established in late 2011 comprising representatives from government agencies, research organisations and the nuclear industry and representing 13 NEA member countries and the European Commission. Information related to national strategies and implementation in represented member countries, along with more specific costing data, were collected through a country questionnaire and constitute the basis of the assessments (qualitative and quantitative) undertaken in the study.[1]

The report does not analyse or reproduce the details of the costing approach used in individual countries or their project management process, nor does it make judgments on the appropriateness of costs derived within a specific national context. Moreover, given the distinctive features and needs of specific national programmes, the results of the cost assessment cannot be simply transposed to individual countries without a more detailed and adapted cost analysis. The analysis presented here aims to assist policy makers in member countries who have specific responsibilities for making strategic choices about back-end options and for ensuring the adequacy of the funding.

In addition to this introductory chapter, the study is composed of three core chapters:

- Chapter 2 develops a descriptive review of the different back-end options and current policies and practices for the management of SNF and HLW, including financing arrangements and considerations related to the cost estimates upon which these are based.
- Chapter 3, which is more analytical, assesses economic aspects, comparatively appraises existing economic models and high-level cost estimates and undertakes sensitivity analyses through a simple model to determine impacts of important variations and key cost drivers.
- Chapter 4 evaluates the influence of other qualitative parameters. Factors selected by the expert group are: security of energy supply, non-proliferation, public attitudes, environmental effects, waste streams, transport of radioactive material, legal and regulatory aspects, development of fast reactors and advanced fuel cycles, retrievability and safety.

Conclusions and recommendations are outlined in Chapter 5.

1. Further information was derived from country profiles (www.oecd-nea.org/rwm/profiles) and reports compiled under the auspices of the NEA Radioactive Waste Management Committee (RWMC), as well as from other sources publicly accessible and duly referenced.

1.3. Types of radioactive waste

Radioactive waste is defined by the International Atomic Energy Agency (IAEA) as "any material that contains or is contaminated by radionuclides at concentrations or radioactivity levels greater than the exempted quantities established by the competent authorities and for which no use is foreseen" (NEA, 2011). In order to facilitate its safe and cost-effective management, radioactive waste is categorised according to the level and nature of its radioactivity and the implications of these properties for its safe handling, transport, storage and disposal (NEA, 2008). While the particular classification systems vary from country to country, general schemes for the classification of radioactive waste are recommended internationally (IAEA, 2007). These take into account the most important radiological characteristics of radioactive waste – namely, the intensity of the radiation and the time needed for that radioactivity to decay to insignificant levels – and the suitable disposal options. The IAEA classification system is described schematically in Figure 1.1 and defined in the box below.

Exempt waste (EW): excluded from regulatory control because radiological hazards are negligible.

Very short-lived waste (VSLW): can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control. This class includes waste containing primarily radionuclides with very short half-lives.

Very low-level waste (VLLW): waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near-surface landfill-type facilities with limited regulatory control. Concentrations of longer-lived radionuclides in VLLW are generally very limited.

Low-level waste (LLW): that requires robust isolation and containment for periods of up to a few hundred years. LLW may include short-lived radionuclides at higher levels of activity concentration and also long-lived radionuclides, but only at relatively low levels of activity concentration.

Intermediate-level waste (ILW): waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided to LLW. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.

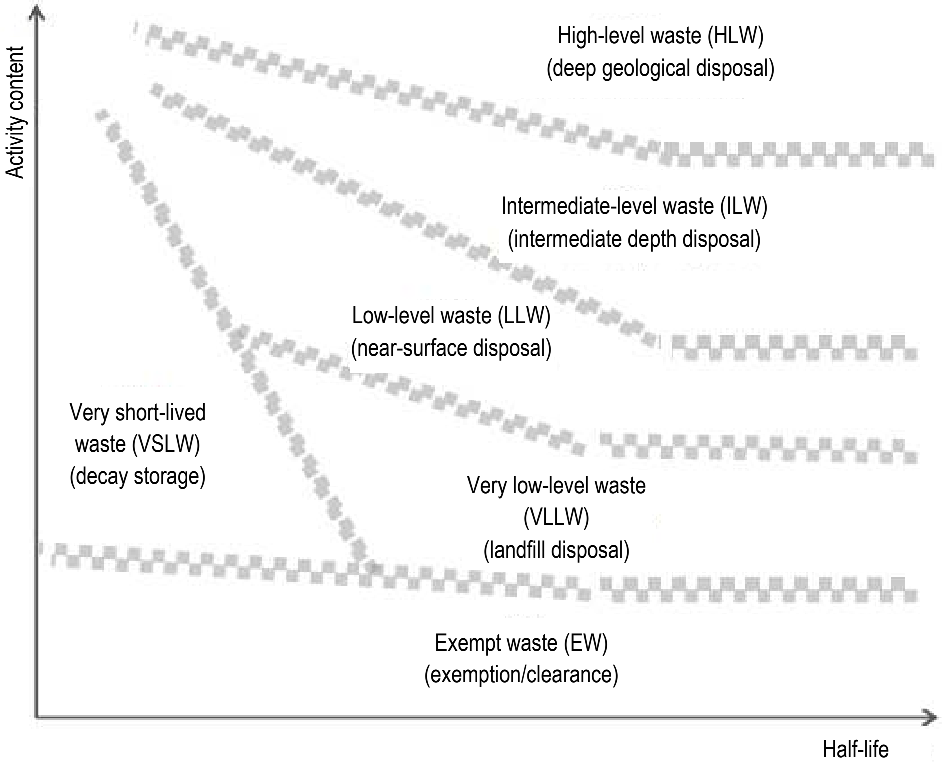
High-level waste (HLW): waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste.

Source: IAEA, 2009.

Internationally, however, most countries still use a previous, slightly different IAEA waste classification system, which combines the activity level of the waste and its half-life. The main categories upon which the system is based are: exempt waste, exempted from nuclear regulatory control (EW), low- and intermediate-level short-lived waste (LILW-SL), low- and intermediate-level long-lived waste (LILW-LL) and HLW. For practical reasons, this older system is adopted in this report. There are exceptions to most radioactive waste classification schemes for the following materials:

- mining and milling waste: residues left from mining and extraction of uranium and other raw materials that contain naturally occurring radionuclides;
- environmental contamination: radioactively contaminated environmental media, such as soil and groundwater.

Figure 1.1: Classification of radioactive waste



Source: IAEA, 2009.

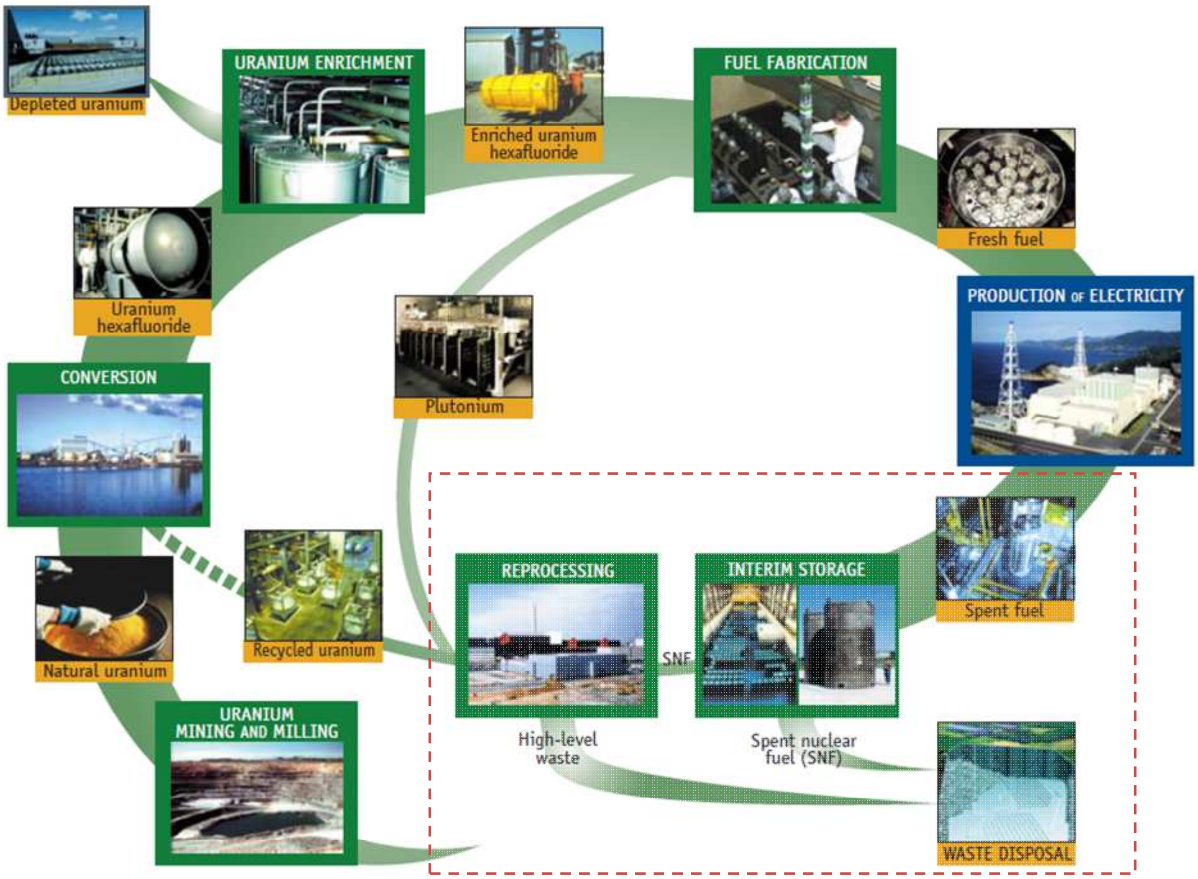
While a wide variety of industries, including medicine, agriculture, research, industry and education, use radioisotopes and produce radioactive waste, the greatest part of civil radioactive waste arises from nuclear power production and the operation of nuclear fuel cycle facilities. After irradiation, spent fuel contains a large quantity of residual fissile material, which is still usable.

Spent fuel could thus be seen as a resource for future use in LWRs or, most efficiently, in fast reactors. Several countries, however, regard this spent fuel as waste, estimating for their national context that the cost of recycling would be too high or not consistent with other priorities, such as non-proliferation policies.

The two fuel cycle options in commercial use at present are the once-through fuel cycle, encompassing the direct disposal of irradiated fuel, and the twice-through fuel cycle which, instead, entails the reprocessing and recycling of the Pu as mixed-oxide (MOX) fuel in LWRs, allowing further utilisation of the residual energy content, as illustrated in Figure 1.2. Recycling of uranium and plutonium in fast reactors are being considered in some countries for future implementation. Several countries, however, have not formulated a final management policy in order to keep open to further technological advances including the use of advanced options for the longer term.

The global annual generation rate of radioactive waste from the nuclear power industry is about 0.4 million tonnes (Mt) plus some 23 Mt of lightly active milling waste from uranium production (NEA, 2010).

Figure 1.2: Schematic view of the fuel cycle with reprocessing and recycling



Only a small part of the waste from power production is HLW,[2] which is almost entirely generated from the fission product residue of reprocessing or the spent fuel for direct disposal. On the other hand, LILW-SL is generated at all stages of the FC. LILW-LL is almost entirely generated by reprocessing.

The large majority of the radioactivity (~97%) is contained in the relatively small volumes of spent nuclear fuel (NEA, 2010) and, for countries that have recycled nuclear fuel, high-level waste from reprocessing. For this high activity and/or long-lived radioactive waste, the consensus in the scientific community is that the best way to achieve long-term management is through disposal in stable geological formations, whose safety relies on containment, isolation and multiple barrier concepts. However, at present, there is no geological disposal facility (repository) in operation in the world for civilian spent fuel and HLW, although good progress has been achieved in some countries (e.g. Finland, France and Sweden), with planned operations in the mid-2020s. The development, implementation and financing of the eventual disposal of spent fuel and high-level waste represent the greatest challenge for the future of radioactive waste management. For this reason, the scope of this study has been focused, in particular, on the long-term management and disposal of spent fuel and HLW, which will be explored in the following chapters. Section 1.4 of this chapter offers an outline of the management of low-level and short-lived intermediate-level waste in NEA member countries.

2. Only about 2% of nuclear power waste is HLW or SF (NEA, 2010).

1.4. Management of short-lived low and intermediate-level waste in NEA countries

Short-lived low-level and intermediate-level waste represents the largest volume of radioactive waste. The technologies for their treatment and storage are well developed and disposal of LILW-SL is an internationally tested practice either in surface facilities (mainly based on engineered barriers to prevent adverse impacts on human health and the environment – NEA, 2010), or in deeper repositories. Most countries with a major nuclear programme operate disposal facilities where LILW-SL waste is already being routinely disposed of[3] (e.g. Finland, France, Japan, Spain, Sweden, the United Kingdom and the United States). Hungary has recently started operation of its Bataapati repository. In other countries disposal facilities are in an advanced stage of planning or construction: Belgium has designated a site at Dessel; in Canada, Ontario Power Generation (OPG), Canada's largest nuclear energy corporation, is proposing to construct a deep geologic repository for its LILW, and the project is currently under regulatory review; in Germany, a repository for non-heat generating waste is being constructed in Konrad; and the Republic of Korea is constructing a repository at Gyungyu. The first underground repository to receive LILW-LL in the world, WIPP (Waste Isolation Pilot Plant, New Mexico, United States) started operation in 1999 for waste generated by the United States Defense Program. Confirming the maturity of LILW-SL disposal technologies, the disposal centre of La Manche in France, which was closed in 1994, continues its planned programme of institutional surveillance with no identified concerns with respect to the safety of the facility (NEA, 2011). An overview of VLLW, LLW and ILW repository sites and projects in selected NEA member countries is provided in Table 1.1 and some are discussed in the ensuing text.

Repositories in different countries meet a wide range of requirements in terms of waste accepted for disposal. Some repositories only accept LLW whereas others accept ILW as well.

Given the short time required for their construction (and hence lower costs), in many countries, (IAEA, 2007a) the preferred option for the long-term management of LILW-SL is disposal in surface or near-surface facilities with varying levels of engineering, including placement in mined or natural cavities some tens of metres below the surface. Underground disposal in rock chambers has been adopted in certain countries, such as the Czech Republic, Finland and Sweden, as it was considered more acceptable by the public (NEA, 2011).

There is considerable regulatory experience in this area that has been shared and contrasted in international organisations like the NEA and the IAEA and that is helping countries that are new to LILW repositories (NEA, 2010).

During the past decade, efforts in LILW management have focused on volume reduction: effective improvements are reported in some countries, with average reductions in the range of 30-50% (NEA, 2011). A second area of development has been the recycling of some forms of waste (e.g. scrap metals arising in large volumes from decommissioning activities) which, after being subject to decontamination and subsequent melting, can be compacted or even used in special systems for the casing of other more active waste.

In some countries, a significant advance in terms of safety and economics has been the establishment of a lower category of waste, identified as VLLW within the wider classification of LILW-SL (NEA, 2011). VLLW is defined as waste that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near-surface landfill-type facilities with limited regulatory control (IAEA, 2009). VLLW disposal sites

3. On a volumetric basis, some three-quarters of all the radioactive waste created since the start of the nuclear industry has already been sent for disposal (NEA, 2010).

can be released some decades after closure, resulting in a significant reduction of costs in comparison with the traditional near-surface vault systems or rock chambers for LILW-SL. This is particularly important when considering the large amounts of waste arising from decommissioning operations. France (at the Morvilliers site, which started operation in 2003) and Spain (El Cabril, which started operation in 2007) have opted for this technology, which is expected to be extended to other countries in the near future.

Table 1.1: VLLW, LILW-SL and LILW-LL repository sites and projects in selected NEA member countries

Country	Site (start year)	Waste category and capacity	Type	Status
Belgium	Dessel and Mol area (TBD)	LILW-SL	ENSF	Public inquiry
Canada	Kincardine (TBD)	LILW-SL and LILW-LL 200 000* m^3	GR	Under licensing /public inquiry
Czech Republic	Richard II (1964)	LILW-SL 8 500 m^3	RC	Operating
	Bratrstvi (1974)	LILW-SL 1 200 m^3	RC	Operating
	Dukovany (1994)	LILW-SL 55 000 m^3	ENSF	Operating
Finland	Loviisa (1998)	LILW-SL	RC	Operating
	Olkiluoto (1992)	LILW-SL	RC	Operating
France	Centre de l'Aube (1992)	LILW-SL 1 000 000 m^3	ENSF	Operating
	Centre de la Manche (1979)	LILW-SL 527 000 m^3	ENSF	Closed in 1994
	Centre de Morvilliers (2003)	VLLW 650 000 m^3	SNSF	Operating
Germany	Konrad (2013)	LILW-SL and LILW-LL (non-heat generating)	GR	Under construction
	Morsleben (1981)	LILW-SL	GR	Closed in 1998
Hungary	Bátaapáti (2009)	LILW-SL	GR	Operating
	RWTDF, Püspökszilágy (1976)	LILW-SL 5 040 m^3	ENSF	Operating
Japan	Rokkasho (1992)	LLW-SL 80 000 m^3	ENSF	Operating
	TBD	LILW-LL	RC	Site-selection
Korea (Rep. of)	Gyungju (2010)	LLW-SL 160 000 m^3	RC	Under licensing
Slovak Republic	Mochovce (2001)	LILW-SL 22 300 m^3	ENSF	Operating
Spain	El Cabril (1992)	LILW-SL	ENSF	Operating
	El Cabril (2008)	VLLW	SNSF	Operating
Sweden	SFR (1988)	LILW-SL 60 000 m^3	RC	Operating
United Kingdom	Drigg (1959)	LLW-SL 1 400 000 m^3	E/SNSF	Operating
United States	Barnwell, South Carolina (1971)	LLW-SL 890 000 m^3	ENSF	Operating
	Richland, Washington	LLW-SL	SNSF	Operating
	Clive, Utah (1988)	LLW-SL and NORM	SNSF	Operating
	Andrews, Texas	LLW-SL and NORM	SNSF	Operating
	WIPP (1999)	TRU (LILW-LL) 175 000 m^3	GR	Operating

* As packaged for disposal.

SNSF = simple near-surface facility; ENSF = engineered near-surface facility; E/SNSF = ENSF and SNSF; RC = rock cavern or intermediate-depth geological repository; GR = deep geological repository; TBD = to be determined, NORM = naturally occurring radioactive material; TRU = transuranics.

Source: NEA, 2008, Table 8.1.

References

IAEA (2007), *IAEA Safety Standards Series for Protection of People and the Environment, Classification of Radioactive Waste*, Draft Safety Guide No. DS 390, International Atomic Energy Agency, Vienna, Austria.

IAEA (2007a), *Low and Intermediate Level Waste Repositories: Socioeconomic Aspects and Public Involvement*, IAEA-TECDOC-1553, proceedings of a workshop held in Vienna, on 9–11 November 2005. Available at www-pub.iaea.org/MTCD/publications/PDF/te_1553_web.pdf.

IAEA (2009), *Classification of Radioactive Waste*, IAEA Safety Standards, IAEA, Vienna, Austria. Available at www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf.

NEA (1999), *Low-Level Radioactive Waste Repositories: An Analysis of Costs*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/1999/low-level-waste-repository-costs.pdf.

NEA (2003), *Nuclear Energy Today*, OECD, Paris, France.

NEA (2008), *Nuclear Energy Outlook*, OECD, Paris, France.

NEA (2010), *Radioactive Waste in Perspective*, OECD, Paris, France.

NEA (2011), *Trends towards Sustainability in the Nuclear Fuel Cycle*, OECD, Paris, France.

Chapter 2. Description of various options and current SNF/HLW management policies

2.1. Industrially available and future options

The back end of the fuel cycle starts when the irradiated or "spent" fuel is unloaded from the reactor. At this stage, spent fuel requires shielding and heat removal, which is achieved through an initial storage in water-filled pools at the reactor site, for periods typically ranging between five and ten years. After this initial period of cooling, during which the highest heat dissipation occurs, the temperature of the fuel is much lower, enabling longer-term management (NEA, 2012). Currently there are two major options in industrial use for the long-term management of irradiated fuel: the "once-through cycle", where the fuel is used once and is then regarded as a waste for subsequent direct disposal, and the partial recycling option where the spent fuel is reprocessed to recover unused uranium and plutonium for eventual recycling in LWRs, partially closing the fuel cycle (NEA, 2011).

The implementation of a spent fuel and radioactive waste management strategy entails a number of subsequent stages, as well as the deployment of various facilities characterised by specific lifecycle phases. A structured identification of such steps and facility lifecycle phases is essential for the selection of a waste management plan and the associated assessments of cost estimates.

Direct disposal	Reprocessing and recycling[1]
• Buffer storage • Interim storage • Encapsulation • Deep geological disposal • Some (2-3) transport steps	• Buffer storage • Reprocessing • MOX and REPUOX recycling • Interim storage of HLW and ILW • Deep geological disposal • Some (4-5) transport steps[2]

1. If recycling is used only partially, there will be a need to also encapsulate and dispose of spent MOX fuel.

2. E.g. Transport of SNF from the buffer storage to the reprocessing plant and transport of Pu from the reprocessing plant to a MOX production plant should be generally considered in addition to the transport steps of the direct disposal option.

2.1.1. Direct disposal

In the once-through (or open) fuel cycle, spent fuel is considered to be high-level waste. Following the initial storage in reactor pools, spent fuel is transferred for long-term storage under wet or dry conditions (as discussed in Section 2.3.2), where it can be kept for at least 50 years before packaging or repackaging becomes necessary or before disposal in an underground repository.

For the ultimate disposal of SNF and HLW, the preferred option continues to be underground emplacement in stable geological formations, in DGRs.[1] DGRs afford long-term safety through the protective functions of the geological environment and the engineered barriers (e.g. a container providing sufficient resistance to corrosion, or, in some cases, a clay buffer) placed around the waste, in addition to the stability of the waste form itself (NEA, 2011). Repositories are typically sited in geological environments and incorporate engineered barriers that offer favourable conditions to protect waste over a long period of time (NEA, 2004). These include environmental features such as mechanical stability, low groundwater flux and favourable geochemical conditions, which should be likely to persist over the relevant very long timescales (NEA, 2007). Robustness of the repository system is favoured by this "multi-barrier" concept. The barriers should be complementary, with diverse physical and chemical components and processes contributing to safety over time, so that uncertainties in the performance of individual components or processes can be mutually compensated (NEA, 2007).

2.1.2. Partial recycling

Irradiated fuel still contains substantial residual energy content, with more than 96% of recyclable material.[2] After irradiation in the reactor there are some 475 to 480 kg of uranium plus about 5 kg of plutonium in a pressurised water reactor (PWR) fuel assembly which, before irradiation, contains approximately 500 kg of uranium (NEA, 2011). The useful uranium and plutonium can be separated from other elements in the spent fuel through reprocessing and utilised through recycling in existing thermal reactors. This allows a reduction of the volume, the long-term heat production and radiotoxicity of the remaining waste to be disposed of, while lowering the supply requirements for natural uranium (approximately 12% reduction can be achieved mainly through the use of residual plutonium and another 10-13% by using the remaining uranium [Greneche, D., *et al.*, 2012]).

Current technologies for the separation of the residual uranium and plutonium from the remaining content of the spent fuel (fission products [FPs] and minor actinides [MAs]) are based on a chemical process known as PUREX (plutonium uranium extraction). The FPs and MAs make up the high-level waste stream. Most of the radioactive materials from reprocessing are immobilised in a glass or ceramic matrix. Non-dissolvable metallic structures of the fuel assemblies constitute another remnant. HLW and packaged metallic structures are then stored, either at reprocessing plant sites or in purpose-built facilities in the country of origin of the reprocessed spent fuel, until disposal facilities become available.

The recovered plutonium during reprocessing is recycled in the form of MOX. Some 10% of reactors worldwide have been licensed to use MOX. The uranium recovered can also be recycled into fuel after re-enrichment. Uranium recycling, however, is only being carried out on a limited scale by some reactor operators, whilst most reprocessed uranium is presently stored for future use. This is because the recovered uranium is more radioactive than natural uranium and hence it requires dedicated enrichment and fuel fabrication facilities to avoid contaminating fresh uranium, which adds to the costs of its reuse.

Spent MOX fuel can itself be reprocessed and the plutonium it contains recycled again. Although schemes are being contemplated by the industry to increase the number of recycles, with current reprocessing and reactor technologies the number of plutonium recycles is in practice limited to two or three (NEA, 2012). This is due to the build-up of

1. As emplacement in deep geological repositories is the solution generally considered for final disposal, thereafter in this document we refer explicitly to DGR to denote final disposal.
2. However, advanced fast reactors and their supporting fuel cycle facilities would be required in order to exploit the majority of this energy in the bulk of the residual ^{238}U.

non-fissile plutonium isotopes, which make it harder to sustain a chain reaction in an LWR. In addition, isotopes of other heavy elements created during irradiation make the fuel material more difficult to process. This limitation on the number of recycles, however, would not apply if the recycled material were to be used in fast reactors. At present, only limited quantities of spent MOX have been reprocessed,[3] and the general strategy is to store it until recycling in fast reactors will be available.

2.1.3. Closing the fuel cycle – recycling in fast reactors[4]

Fast reactors are more suited for multi-recycling of fissile and fertile materials as they operate in fast neutron spectra, where fertile isotopes can be transformed into fissionable materials allowing a more effective use of the uranium resource. The depleted uranium from the enrichment process can be used as the fuel for fast reactors where all actinides could also be recycled continuously until they fission, allowing the full closure of the fuel cycle. However, even for closed fuel cycles there is the need to manage residual actinides (from losses) and fission products, since the process is not completely efficient.

The deployment of fast neutron systems and eventually the transition from thermal reactors to fast reactor fleets will require significant efforts of adaptation, including in legal and regulatory frameworks, increased investment and the development of new infrastructures for advanced systems and processes (see also Section 4.8).

Many countries have already devoted extensive efforts to the research and development of advanced reprocessing methods. These have often been aimed at the development of advanced processing techniques for the separation (partitioning) of minor actinides for their subsequent transformation (transmutation) into shorter-lived elements, either in fast reactors or in accelerator-driven systems. Research and development on advanced separation methods has also been driven by the interest in process optimisation and enhancement of proliferation resistance features by moving towards technologies that do not extract pure plutonium.

It should be noted that, even in advanced options and regardless of the fuel cycle strategies adopted, a deep geological repository will be necessary to dispose of either HLW or spent fuel (treated as HLW in the once-through fuel cycle); hence, progress towards implementation of deep geological repositories remains a high priority for the use of nuclear energy.

2.2. General principles and frameworks

2.2.1. Principles

There are generally agreed principles underlying the management of radioactive waste and spent fuel that embrace safety and ethical imperatives (see e.g. NEA, 2006). The prime objective of any option is achieving and maintaining high levels of safety in the long-term management of spent fuel and radioactive waste, so that individuals, society and the environment are protected against potential hazards and from harmful effects of ionising radiation over time. Key ethical pillars are the "intergenerational equity" and the "user/polluter pays" principles (further discussed, along with other principles, in Appendix 1), which also raise specific financial obligations. The legal basis for the establishment of adequate funds lies on these principles, along with a number of additional criteria including: sufficiency, availability and transparency (see also NEA, 2006). Another aspect of funding SNF and radioactive waste management from the income of nuclear power production is to ensure that the real cost of power production is assessed by including also future costs.

3. Approximately 70 tHM of MOX have been reprocessed at La Hague.

4. See NEA (2011) for details.

With regard to the construction and operation of back-end facilities, social acceptance is also a central principle (this is further considered in Sections 2.3.3 and 4.4). Any facility should be designed in a way that it is acceptable to the public, and especially to those communities in proximity of the siting zone, without imposing undue burdens on future generations.

2.2.2. International instruments

The principles introduced above form the basis of international legal instruments developed and adopted in relation to the management of spent fuel and radioactive waste:

- The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (IAEA, 1995) is the first international treaty on safety in these areas. It represents a commitment by participating states to achieving and maintaining a consistently high level of safety in the management of spent fuel and of radioactive waste to ensure the proper protection of people and the environment.
- Following a recommendation and a guide on the management of financial resources for the decommissioning of nuclear installations and the handling of spent fuel and radioactive waste (EU 2006a, b), the Council Directive 2011/70/Euratom (as promulgated on 19 July 2011 [EU, 2011]) "establishing a community framework for the responsible and safe management of spent fuel and radioactive waste". The directive sets out requirements for European countries to develop and maintain a national framework that ensures the provision of appropriate national arrangements for a high level of safety in spent fuel and radioactive waste management, protecting workers and the general public against the dangers arising from ionising radiation.

Safety is at the heart of both international instruments, which also contain provisions relative to transparency and public participation, financial resources to cover the cost of radioactive waste and spent fuel management, training and obligations concerning regular self-assessments and peer reviews.

2.2.3. National legislation

Appropriate national arrangements are well established in most countries with advanced nuclear power programmes or are otherwise being implemented by states for the management of SNF and waste generated in their territory, including the definition of policies and strategies and the development of national legislation. These are in compliance with the internationally acknowledged principles considered above and the requirements set out in the associated international instruments, which, when transposed into the national legislation, become legally binding.

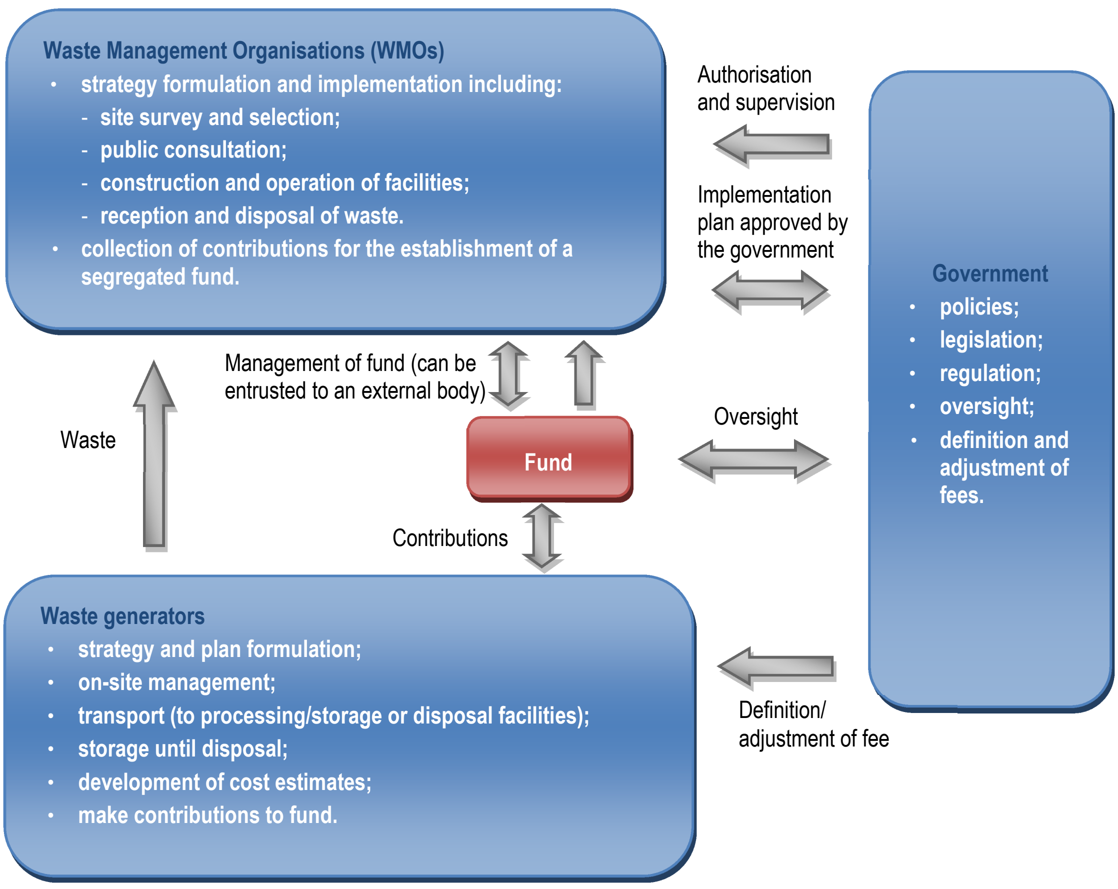
Legal and institutional frameworks are required to ensure that polices and strategies are adhered to. These prescribe, *inter alia*, the establishment of the necessary funds, their safeguard against mishandling, inappropriate claims or use (e.g. in case of financial instabilities), their adequate administration (including consideration of inflation and escalation), and, in case of shortage, the provision of financial guarantees.

Liability management entails the identification and adequate allocation of financial and non-financial responsibilities that need to be fulfilled today in order to provide for the safe, final management of radioactive materials when the time arises for this to take place. If these tasks are discharged correctly, no residual liability should exist in the end (NEA, 2003).

As activities related to the management of SNF and radioactive waste involve very extended times which can span several generations, it is important that adequate and sufficiently durable provisions are made to ensure the continued fulfilment of responsibilities and funding requirements. The consequences of an inadvertent break in the continuity of technical capability or availability of funding through transfer of ownership might have important impacts (NEA, 2008).

Key players are the waste producers, the government and specialised national waste management organisations (WMO, as they are often referred to), which are given charge of the long-term safe management of radioactive waste, as well as the regulatory body. WMOs can hold various responsibilities, from the centralised collection of SNF/waste and the related processing capabilities, to the final disposal. WMOs can be either state organisations, who take over the full responsibility for the technical implementation and in some cases also for funding, or organisations related to the waste generators, set up to practically implement the responsibilities of the generator. One example of institutional framework and associated responsibilities is illustrated in Figure 2.1, while responsibilities typically attributed to individual stakeholders are further discussed in Appendix 1.

Figure 2.1: Example of institutional framework and associated responsibilities



The legal ownership of the spent fuel or radioactive waste might change during the process of implementation of a country's national strategy and interfaces may vary according to the specific roles allocated to various parties. The responsibility for the SNF/HLW by waste generators may end at the time of disposal, cease before, or it may extend beyond (e.g. after closure of the permanent disposal, including monitoring), depending on the interface between the waste generators and the waste management organisation. For instance, in France waste producers remain ultimately responsible for nuclear waste and SNF and in Finland they shall bear all the costs of radwaste up to its disposal, including monitoring costs of repositories after their closure; whereas, in the Czech Republic NPP operators are held accountable for the handling SNF/radwaste up to final transportation to a central SNF repository; and in Spain the state shall take over the ownership of radwaste once this is definitively classified as a waste and disposed of.[5]

2.3. Policies, implementation and financing arrangements in NEA member countries

The following sections consider the national outlook of SNF and HLW management for NEA member countries, in terms of their policy stances (Section 2.3.1), progress in the implementation of their programmes (Section 2.3.2) and, more specifically, public involvement (Section 2.3.3) and funding arrangements set up to meet associated financial liabilities (Section 2.3.4). A more succinct discussion on policies and progress on SNF/HLW management is provided in Section 2.4 for some non-OECD/NEA member countries.

2.3.1. Policies

While a national policy for SNF and radwaste management should be compatible with the general principles and international instruments of relevance described in Section 2.2.1, its definition is inevitably influenced by numerous other factors which are often country specific (as further discussed in Chapter 4). Such a policy must be coherent with other, non-nuclear policies, in particular those dealing with other hazardous materials; it must reflect national priorities, circumstances, structures, human and financial resources, as well as the type and characteristics of the radioactive waste, its geographical distribution and that of the population (IAEA, 2009). Both existing and planned or anticipated developments in the field need to be considered together with the magnitude and scale of the hazard posed by the waste.

As regards SNF management, traditionally there has been a clear divide between countries that have adopted a national reprocessing policy and those who have not (NEA, 2011). Appendix 2 gives a synopsis of the country choices together with some details of their evolution over time. Reprocessing policies have been sustained in France, Japan, the Netherlands, the Russian Federation and the United Kingdom, and, among non-OECD/NEA member countries, the People's Republic of China and India. With the exception of the Netherlands all these countries hold commercial reprocessing facilities (France, the Russian Federation and the United Kingdom[6]), or have been intending to move from pilot to commercial reprocessing plants (Japan, the People's Republic of China and India). Table 2.1 indicates the reprocessing capacities held and projected in various countries. In France, as in Japan, the motivation to utilise MOX fuels or reprocessed

5. Concerning the nuclear facilities to be dismantled, the licence, not the ownership, of such facilities is transferred to ENRESA, the waste management organisation, to perform the decommissioning and dismantling works, including the required surveillance thereafter. After this surveillance period, and in accordance with the Spanish Nuclear Authorities, the use of the property will be given back to the owner and released for further uses.

6. In the United Kingdom, reprocessing facilities will be closed once all current contracts for the reprocessing of spent is completed by 2018.

uranium has been to reduce natural uranium needs and ultimate waste volumes, whilst pursuing improved characteristics for the waste. In France, the use of recycled material in LWRs has increased markedly in recent years, with an estimated contribution to nuclear generation coming from recycled products amounting to approximately 17% in 2012 (WNA, n.d.) (21 French NPPs are currently using MOX and 4 NPPs are licensed to use REPUOX – reprocessed uranium oxide). With a view to securing the autonomy of nuclear fuel cycle activities, Japan has pursued the construction of Rokkasho Reprocessing Plant and a MOX fuel facility close to the reprocessing plant to reprocess SNF within its territory.[7] In the Russian Federation, the policy for spent fuel management has also been based on the principle that SNF is not radioactive waste, but a valuable source for producing nuclear fuel components and a number of radioactive isotopes used in medicine, agriculture and industry. In these countries, the preferred option is to later reprocess also irradiated MOX fuel assemblies to provide fissile and fertile material for the fast reactors under development.

Table 2.1: Reprocessing capacity (civilian) in the world

Country	Fuel type	Capacity (tonnes/year)	
		2010	Projected (mixed fuel type)
China, People's Rep. of	LWR	50[1]	800
France	LWR/FR	1 700	1 700
India	PHWR	260	300 (under construction)
Japan	LWR	120	800 (under construction)
	LWR/FR	40	40
Russian Federation	LWR/FR	400	~1 400
United Kingdom[2]	LWR	900[3]	N/A
	Magnox	1 500	N/A

1. Pilot (50 t/year) reprocessing plant at Lanzhou Nuclear Fuel Complex (see www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Fuel-Cycle).

2. The United Kingdom is planning to shut down their reprocessing facilities in the next few years.

3. This figure is taken from NEA (2010) – the design capacity for LWRs (Thermal Oxide Reprocessing Plant – THORP) is 1 200 tHM/year.

PHWR = Pressurised heavy water reactor; N/A = not applicable.

Some other countries have used MOX fuel in their LWRs in order to fulfil obligations to consume plutonium from historical reprocessing contracts. In these cases, generally, the irradiated MOX fuel assemblies would then join irradiated UO_2 assemblies for interim storage and eventual geological disposal. Historically Belgium, Germany and Switzerland had significant amounts of their spent fuel reprocessed. However, policies in these countries have changed over time. For example Germany moved to direct disposal in the 1990s, after having been fully committed to reprocessing, with reprocessing contracts with facilities in France and the United Kingdom (UK), advanced plans to build a reprocessing plant at Gorleben and ongoing testing of recycling as MOX fuel. A similar shift occurred in the UK (see also NDA, 2012), where the spent fuel management policy is that its radwaste management is a matter for the commercial judgement of its owners, subject to meeting the necessary regulatory requirements, whereas the historical

7. However, after the accident at the Fukushima Daiichi NPP, Japan's entire energy policy is under review, including the future of reprocessing.

approach (since the 1960s) had been to reprocess spent fuel in facilities at Sellafield.[8] Most of the UK's spent fuel from civil reactors has been or is contracted to be reprocessed. However, some spent fuel from existing UK advanced gas-cooled reactors (AGRs) and all the spent fuel from Sizewell B PWR is not currently destined for reprocessing. Furthermore, by 2018, all current contracts for the reprocessing of spent fuel in UK-based reprocessing facilities will be completed, and so these facilities will be closed. The utilities involved in the anticipated 16 GW new reactor build programme for the UK have all assumed disposal of their uranium oxide spent fuel arisings in their planning applications. For the specific purpose of managing civil separated plutonium stocks,[9] the UK government, in its response to the public consultation launched in 2011, indicated that pursuing reuse of plutonium as MOX would be the preferred solution (DECC, 2011). To date no commercial MOX fuel has been used in UK NPPs.

On the other hand, Canada[10], Finland, Spain, Sweden and the United States are countries where either an early decision was made not to reprocess or where reprocessing policies were abandoned early on. In Nordic countries' (Finland and Sweden) policies for spent fuel management have been oriented consistently, since the 1980s, to direct disposal of spent fuel in underground repositories. In both countries SNF from the reactors is stored for interim storage (in a centralised facility in Sweden and at reactor sites in Finland) prior to its permanent disposal in a deep geological repository. Long-term continuity in policy stances in Finland and Sweden has been reflected in a significant advancement of disposal programmes (further discussed in Section 2.3.2).

A number of countries have been holding off from developing a firm or single strategy and have not formulated a final policy for disposal. In the Netherlands a delayed geological disposal is planned. The policy is based on a stepwise process in which all decisions are taken to ultimately ensure safe disposal in a repository, but without excluding alternative solutions in the future. In the meantime all radioactive waste is collected in interim storage designed for storage for at least 100 years. This policy was not taken as a "wait-and-see" option. In principle, the decision for reprocessing is left to the nuclear operator, and although to date no MOX fuel has been burnt in Dutch NPPs, the Borselle plant has been licensed for its use.

In Spain the National Policy is set up in the General Radioactive Waste Plan (GRWP, 2006), which, in its current revision, contemplates several base options for the adoption of a national long-term management policy. These include limited (~50 to 100 years) and prolonged (>100 years) temporary storage of spent fuel followed by a definitive disposal facility, as well as temporary storage followed by reprocessing (with possible variants with partitioning and transmutation) followed by temporary storage and a definitive disposal facility for HLW. However, for the purposes of the Spanish Policy, the preferred basic option is limited temporary storage of spent fuel followed by definitive disposal (around 2060).

Although no final decision for the long-term management of spent fuel has been taken in the Republic of Korea, deep geological disposal is currently envisaged. Recycling by pyroprocessing is also considered. At present SNF is stored at reactor sites pending construction of a centralised interim storage facility by 2016.

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8. The Thermal Oxide Reprocessing Plant (THORP) was commissioned in 1994 and has treated used LWR fuel for overseas and domestic customers, while the Magnox Reprocessing Plant, opened in 1964, has treated used Magnox fuel. Both plants are due to close by 2018.

9. The United Kingdom has a significant stock of civil, separated plutonium from historic reprocessing operations.

10. Canada has policies, legislation and organisations in place to provide for the safe and secure management of radioactive waste. The Nuclear Fuel Waste Act, passed by parliament in 2002, is a framework to address the long-term management of nuclear fuel waste in Canada. Canada's 1996 Radioactive Waste Policy Framework defines stakeholders' responsibilities.

In the United States, the current legislation requires direct disposal. Commercial SNF is currently being managed at reactor sites, SNF and HLW owned by the Department of Energy (DOE) at DOE sites, with no disposal facilities planned to date. Following the abandonment of the Yucca Mountain project, in 2010 the Secretary of Energy established a Blue Ribbon Commission (BRC) on America's Nuclear Future to evaluate and make recommendations on alternative approaches for managing SNF and HLW from commercial and defence activities. At the end of January 2012, the BRC released a final report (BRC, 2012) articulating a set of consensus recommendations for public review and comment. Some of the key elements for the recommended strategy reached by the commission include: directing prompt efforts to develop one or more geological disposal facilities, consolidating storage facilities and preparing for the eventual large-scale transport of SNF and HLW to such facilities when they become available; adopting a new, consent-based approach to siting future nuclear waste management facilities; establishing a new organisation dedicated solely to implementing the waste management programme and empowered with the authority and resources to succeed; granting access to the funds that nuclear utility ratepayers are providing for the purpose of nuclear waste management. In January 2013, the DOE announced the waste disposal strategy (DOE, 2013) elaborated by the administration to move ahead with the recommendations of BRC. The document outlines a framework for moving toward a sustainable programme for the deployment of an integrated system which would provide storage, disposal and transportation of SNF and HLW from civilian nuclear power generation, defence, national security and other activities. The strategy includes a phased, adaptive, and consent-based approach to siting and implementing a comprehensive management and disposal system. The system planned entails a pilot interim storage facility, a larger, full-scale interim storage facility and a geological repository, to be available respectively by 2021, 2025 and 2048. The facilities could be co-located in any combination or sited separately and, while the strategy is focused on just one of each facility, more than one storage facility and/or repository may be considered, depending on the results of the consent-based siting process (DOE, 2013). The strategy supports progress on legislation on the back end of the fuel cycle, which would represent a crucial step forward for nuclear power in the United States.

International approaches are also being envisaged for the disposal of SNF and HLW (NEA, 2011). The concept of regional and international repositories represents an attractive solution, from the economic, technical and environmental perspectives, particularly for countries with small nuclear programmes, although it raises challenging political and public opinion issues. With regard to the management of recyclable fissile and fertile materials, transnational concepts include the deployment of facilities, at the multinational, regional and/or international level, which would not be viable, technically and economically, at the national level in all countries running or envisaging a nuclear programme. Another emerging prospect is the fuel leasing concept, which means that the SNF will be taken back to the country that originally supplied the fuel. This latter option is being proposed by the Russian TVEL through a combined offer of front- and back-end services to new-comer countries that could reduce their need to establish domestic back-end infrastructures. Transnational solutions, albeit politically sensitive, could result in optimised options which, while limiting the spread of sensitive technologies like enrichment and reprocessing, may lead to a reduction of costs through scale effects.

2.3.2. Current progress

Interim storage

Interim storage is a key step in the back end of any fuel cycle, needed for the decay of radioactivity and heat output of spent fuel and HLW, before enacting the following step or process of the strategy. Long-lived solid radioactive waste and SNF have been safely and securely stored in NEA member countries now for several decades.

The two main options adopted so far for interim storage are pool storage and dry storage (both either at reactor or at centralised sites). Wet storage in pools next to the reactor is generally adopted during the first years after discharge to allow cooling (NEA, 2011). With the greater use of MOX and high burn-up fuels resulting in higher decay heat levels, this praxis will probably be adopted for longer times (IAEA, 2009a). Pool storage is also often used at reprocessing plants as it facilitates easy retrieval of specific fuel assemblies for batch reprocessing. France, Japan, the Russian Federation, and the United Kingdom have centralised pool storage of SNF to support their associated reprocessing plant operations (MIT, 2011). In some countries pool storage facilities are used for long-term interim storage too, e.g. in Finland and Sweden.

After sufficient decay of fission products and especially where long-term storage is foreseen (up to and beyond 100 years), dry storage under inert conditions or in air is nowadays generally the preferred option, mainly in casks, but also in vaults. This modular technology is often used to complement the capacity of NPP pools, providing a system of easy implementation and low operational costs. In the last decade there has been an apparent trend to use commercially available dry storage systems, and also to implement centralised storage facilities for HLW and spent fuel (NEA, 2011). This is partly due to economic considerations and partly to political decisions, the latter often related to delays in implementing ultimate disposal, and to better assess the potential implications of technologies under research and development (R&D) in the implementation of national strategies. Expected storage times can vary significantly (NEA, 2008) and may extend for many decades, provided adequate controls and supervision are in place, combined with repackaging of some waste and periodic refurbishment of stores if needed (NEA, 2006a).

However, there can be a trade-off between the cooling period adopted and the repository design, influencing the timing of disposal. De facto longer-term interim storage is an increasingly adopted practice, due to extended times for the deployment of final repositories, or as a result of a considered strategy choice. While in most cases, interim storage facilities were initially designed to operate for periods up to 50 years, now operational periods of 100 years or longer are increasingly being considered. A noteworthy example is that of the Netherlands, where the radioactive waste and SNF will be stored for a period of at least 100 years above ground. Some examples of interim storage facilities are reported in Table 2.2, with some details on the type of approach adopted, the expected storage time, capacities and costs, when available.

Reprocessing and MOX recycling

Irradiated nuclear fuels were first reprocessed in the 1940s using pyrochemical and precipitation processes. These separation methods were soon replaced by the solvent extraction process (hydrometallurgy), which is better suited to continuous, large scale, remote operation, allowing for the separation of three main streams of nuclides (uranium, plutonium and waste, i.e. FP and MAs). Different solvent extraction systems were explored but the combination known generically as PUREX (which utilises the extractant tributyl phosphate mixed in a largely inert hydrocarbon solvent) soon replaced all earlier solvent extraction media because of its high performance in industrial scale plants. The PUREX process was used for several decades in the production of separated plutonium for military purposes, but in the 1970s industrial implementation of the process was further extended to reprocess fuel coming from commercial reactors (initially gas-cooled reactors, later on from LWRs and then pressurised heavy water reactors [PHWRs]).

Table 2.2: Examples of separate interim storage facilities

SNF/ HLW	Storage facility type and concept		Country	Facilities	Expected storage time	Planned extension (yes/no)	Capacity	Cost in USD millions OVC(1)	O&M(1)
SNF	Immediate storage for cooling and after unloading of reactor		All SNF is cooled under water after its unloading from reactor		Months to years	In several cases			
	At reactor	Dry storage	Belgium	Doel			Not available		
			Canada	Operating dry storage facilities, of various designs, at each of the nuclear sites, (including OPG facilities, Pt Lepreau, Gentilly 1 and 2, and various AECL facilities).	50 years	Yes – plan to double current capacity	Total amount of used fuel currently in dry storage 16 500 tHM	~2 805	
			Czech Republic	Dukovany Temelin	60 years		3 310 tHM(2)	Not available	
			Korea (Republic of)	Wolsung	50 years	Yes	6 237 tHM	Not available	
			Spain	José Cabrera – PWR (under D&D) Trillo – PWR Ascó – PWR (commissioning in April 2013)	Up to ATC availability	No	124 dry casks	Not available	
		Wet storage	Belgium	Tihange			Not available		
			Finland	Loviisa	up to 2068	No	620 tHM	Not available	
				Olkiluoto	up to 2114	Yes	1 555 tHM		
			Switzerland(3)	Gösgen NPP		Yes	600 SNF elements – being expanded to 1 600	Not available	
	Central		Sweden	CLAB Oskarshamn	~40 years	Possible(4)	8 000 tHM	888	1 734
			Russian Federation (Stoller, 2012)	VVER and RBMK NPPs At the Mining and Chemical Combine Zheleznogorsk			8 400 tHM VVER	Not available	
			United Kingdom	THORP Receipt and Storage	up to ~2075 pending disposal		400-6 000 tHM AGR SNF	(5) ~300	~33/year

See notes on page 40.

Table 2.2: Examples of separate interim storage facilities *(continued)*

SNF/ HLW	Storage facility type and concept		Country	Facilities	Expected storage time	Planned extension (yes/no)	Capacity	Cost in USD millions	
								OVC(1)	O&M(1)
SNF	Central	Dry storage	Japan	Recyclable Fuel Storage Centre, Mutsu City (construction started in August 2010)	50 years		~5 000 tHM (total)	Not available	
			Korea, Republic of (to be deployed)	PWR	50 years		12 000 tHM	1 124	1 006(6)
				CANDU			8 000 tHM	~180	337
			Russian Federation(7)	Zheleznogorsk	~50 years pending reprocessing	7 800 tHM additional capacity (VVER1000) by 2016 15 000 tHM additional capacity (RBMK) by 2020	8 100 tHM RBMK fuel	~500	
			Switzerland(2)	ZWILAG			200 SNF and HLW casks	Not available	
			United Kingdom	Vitrified Product Store	up to ~2075 pending disposal			Not available	
SNF + HLW			Spain (to be deployed)	ATC – centralised temporary storage facility (dry vault) (site selected late 2011)	2017-2070 (~100 years design life)	No	7 000 tHM (also for ILW)(8)	1 589	794
			Netherlands	HABOG	>100 years	Yes	270 CSD-Cs 70 SNF canisters	Not available	
HLW	Dry storage of vitrified HLW		Belgium	Dessel Building 136 (also for ILW)	Up to 2100(9)	Yes	HLW: 590 canisters (106 m³)	~612(10)	~50(10)
			France	La Hague	30-50 years		Not available		
			Japan	Vitrified Waste Storage Centre of JNFL (storage pits)	30-50years		Not available		

Source: Data are derived from responses received by member countries to the country questionnaire, unless otherwise specified.
1. OVC = overnight investment costs; O&M = operation and maintenance.
2. 600 tHM (ISFS Dukovany) + 1 340 tHM (SFS Dukovany) + 1 370 tHM (SFS Temelin).
3. See country profile at www.oecd-nea.org/rwm/profiles/Switzerland_profile_web.pdf.
4. Clabs capacity can be extended if required, at a first stage to 10 000 tHM through a better utilisation of existing pools, at a second stage up to 15 000 tHM by building a new rock chamber adjacent to the two existing ones.
5. Corresponding respectively to ~GBP 140 million and GBP 33 million/year (conversion obtained using OECD statistics).
6. Including: Operational costs of storage facilities; transport container and vehicles; transport facilities (harbour, etc.); operational costs of transport facilities; and R&D.
7. Source: Stoller, 2012.
8. ~20 000 FAs + 1 000 m^3 of LL-ILW.
9. Provided refurbishment operations are undertaken.
10. Corresponding to overnight investment and O&M costs of, respectively ~EUR 420 million and ~EUR 34 million.
D&D = decommissioning and dismantling.

Initially the recycling of plutonium in the form of MOX fuel (UO_2-PuO_2 or MOX fuel) in fast breeder reactors was regarded as the standard strategy, but the prospects for fast reactor (FR) implementation to close the fuel cycle were progressively postponed, as in the 1980s the worldwide development in nuclear energy turned out to be more modest than expected. Nonetheless, several countries, including France, India, Japan, the Russian Federation and the United Kingdom, carried on developing, continuously improving and adapting the PUREX technology (in France for the MOX fuel fabrication, in the Russian Federation for U recycling in RBMK fuel, in India for the U recycling in PHWR fuel and MOX for fast breeder reactors).

Modifications to the PUREX process have lately been developed primarily to improve performance, e.g. reducing the amount of secondary waste arising, while also allowing the treatment of a larger variety of fuels (e.g. fuels with higher burn-up, different compositions, etc.) (NEA, 2011).

To date mono-recycling of plutonium is carried out in some 40 NPPs in the world to partly realise its energy potential, while stabilising the plutonium inventory. With the significant irradiation experience accumulated, the use of MOX can be regarded as a mature technology, fully established industrially. MOX fuel performance has matched the excellent record of uranium oxide (UOX) fuel assemblies reaching parity, in most instances, also in terms of high discharge burn-ups (NEA, 2011). Several decades of industrial feed-back in the development of the PUREX process have led to a continuous decrease of solid waste volume, effluents and environmental impact in terms of radiation doses (NEA, 2011). The most advanced MOX recycle programme in PWRs is running in France, where, still seen as a valuable intermediate stage on the way to full recycle in fast reactors, this practice has recently seen a considerable extension, with the following perceived benefits (WNA, n.d.):

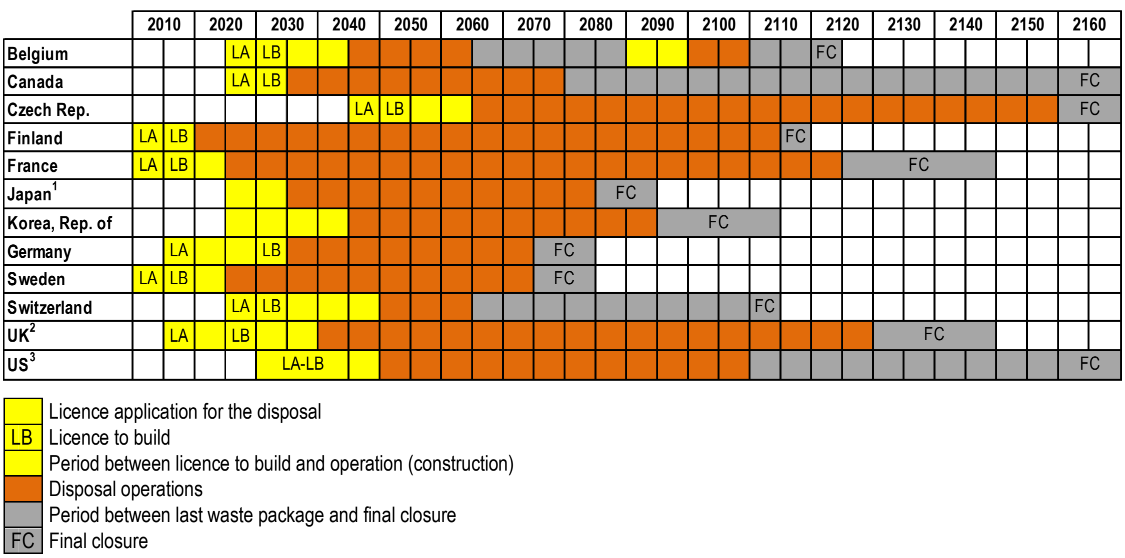
- Minimisation of the stored inventory of separated plutonium: plutonium recovered from the reprocessing plants is recycled as MOX and any remaining plutonium in the subsequently discharged spent MOX fuel is subject to a high degree of self-protection from the radiation field, reducing proliferation risks.
- At equilibrium, the use of MOX in LWRs gives typically a reduction of about 12% in immediate uranium requirements, also helping to hedge against uranium price fluctuations.
- Use of MOX in LWRs demonstrates elements of recycling technology that will be required later for full recycle in fast reactors.
- Interim storage of the irradiated MOX fuel assemblies constitutes a reserve of plutonium that in the future can be reprocessed to feed the initial cores of a fast reactor fleet.
- Due to the reprocessing of the original UO_2 fuel, an improved ultimate waste matrix is obtained, which may have advantages for geological disposal in the very long term; waste volumes and long-term heat production and radiotoxicity are also reduced, alleviating requirements for long-term safeguarding of the disposed waste.
- For countries using existing reprocessing facilities, the need for national longer-term interim storage is alleviated and investment needs for additional back-end facilities reduced.

Multi-recycling of fissile and fertile materials can be achieved in fully integrated cycles of fast reactors, which could combine waste minimisation with the optimisation in the use of natural resources. As mentioned in Section 2.1 and further discussed in Section 4.8, many countries have undertaken extensive research and development on advanced systems and fuel cycles including fast reactors; but their commercial deployment is still some way away.

Implementation of deep geological repositories

An overview of country programmes for the implementation of deep geological repositories is provided in this section; progress of some specific country programmes is discussed, in some more detail in Appendix 3, which also provides certain features considered in countries DGR designs. National programmes are at very different stages around the world and, as yet, no country has succeeded in opening a repository. Nonetheless some good advances have occurred and a few countries are successfully proceeding with their long-term plans to develop repositories. Notable examples are Finland, France and Sweden, where operations of the respective national DGRs are planned to begin around 2020-2025. Other national programmes including those of Canada, Germany and Japan are planned to follow, with target DGR in-service dates by 2035-2040. In several countries such as Germany, the United Kingdom and the United States, plans to develop geological repositories have suffered from public and political opposition, leading to important programme delays (NEA, 2012). The timing of the steps towards the implementation of final disposal in some NEA member countries is reported in Table 2.3. Planned in-service dates will depend, however, on the completion of key milestones such as the confirmation of disposal concepts, site selection, the issuance of safety requirements and positive licensing decisions (NEA, 2010).

Table 2.3: Disposal time frames for DGRs in NEA countries (as considered in cost estimates)



1. Data are based on JAEC (2011).

2. Data are provided by the NDA's Radioactive Waste Management Directorate (RWMD) and based on NDA (2010). This reflects the UK position in 2010. There may be some delays as part of the UK government's ongoing review of the Managing Radioactive Waste Safely (MRWS) process.

3. Data are based on DOE (2013).

Typically a stepwise approach is adopted for the implementation of the programmes and in particular the selection of the site. Staged plans often commence with preliminary investigations for initial identification of suitable siting areas, with open solicitation of local communities which are involved on a basis of voluntarism and partnership. Following identification of a few candidate sites, further more in-depth investigations are conducted towards the down-selection of the sites and the finalisation of the project. With increased stakeholder engagement at the different stages and the move to partnerships with potential host communities, this approach has engendered an improved public acceptance in some countries (see also Section 2.3.3).

Legal and institutional frameworks have been established or further strengthened (as discussed in Section 2.2.3) and safety analyses have been or are being developed in several countries for DGR designs. Safety assessments are being regularly reported and in many cases (e.g. Belgium, France, Sweden and Switzerland) peer reviewed internationally. The increased use of international peer reviews is seen as a mechanism to evaluate the approach used for safety demonstrations in developing disposal facilities.

Technological developments in the design of geological repositories have continued. In several cases "staged disposal concepts" have been implemented, leaving the decision to finally close and seal the repository to be taken many years into the future (NEA, 2007b). During the time when the repository remains open with continued monitoring, the waste would be in a state that allows fairly easy retrieval, should this prove necessary. This approach enhances confidence in the disposal method and enables stepwise decisions to be made in the light of experience gained during the life of a repository, rather than committing to a particular course of action right from the start.

Often reversibility and retrievability have been included in recent design developments of geological repositories impacting specific requirements (NEA, 2011). As further discussed in Chapter 4, these features are fundamentally motivated by three considerations: the possibility of benefiting from future scientific and technical progress; the potential economic valuation of the waste; and the ethical mandate of providing freedom of decision to future generations. Among countries interested in pursuing retrievability and reversibility, several stances have been adopted, mostly during the last few years (NEA, 2011). The Netherlands was the first country to require retrievability of geological disposed radioactive waste by law: in the 1990s the Dutch national research programme on disposal of radioactive waste, carried out under the scientific supervision of the Committee on Radioactive Waste Disposal (CORA), was mainly focused on adapting existing repository designs and showing that retrievability requirements would not jeopardise long-term safety. Also in France, Switzerland and the United States, retrievability is required by law and it is stated in government policies in Canada and Japan. In Finland and Sweden, these features are simply built into the DGR design and they are part of the current national debate in the United Kingdom.

Each national programme tends to concentrate its effort on a particular type of rock. Granite, clay, salt and tuffs are the most frequently selected rock formations. Most countries have retained their preferred host rocks since the very beginning of their research programmes (Belgium, Canada, Finland, France, Germany, Sweden, etc.), whereas some have changed. Switzerland has had a significant shift in the last 20 years from mainly working with granites to more recent research totally oriented to clay. The Netherlands focused solely on rock salt as promising indigenous host rock to house a repository for radioactive waste until the early 1990s.[11] Although that option has not been abandoned, since then focus slowly shifted towards clay as host rock, merely to bring the amount of knowledge to the same level.

The different physical and technical conditions that apply to different host rocks have an impact on the costs of the DGR (NDA, 2012a). For instance, in the United Kingdom, initial cost estimates have focused on three different geological environments for planning purposes: higher strength rock, lower strength rock and evaporates. These show that, for the same inventory, indicative costs for the implementation of a design concept

11. This shift started in the 1990s in the national CORA programme, in which available information concerning deep disposal in either host rocks was compared. One of the many findings of that programme was that deep disposal in a repository in clay might be twice as expensive as one in rock salt (CORA, 2001).

in lower strength rock are expected to be about 30% more expensive than what is estimated for higher strength rock and evaporate rock (GBP 16 billion versus GBP 12 billion at 2008 money values and undiscounted). The increase in cost for a lower strength rock facility is due to the smaller underground openings that would have to be used, which results in more numerous openings required for the same waste inventory. Furthermore, additional costs to support and maintain the infrastructure and emplacement of facilities would be required, along with extra equipment. Similarly, comparative estimates conducted in Japan for soft and hard-rock environments also indicate greater costs for the former (JAEC, 2011).

2.3.3. Public involvement[12]

In modern society, public acceptance has become increasingly central for the successful implementation of large infrastructure or, in general, projects and technologies which are seen as bearing inherent risks. Governmental decisions taken in this respect, require greater focus to societal aspects, while, in former times, they may have been taken principally on technical grounds (*albeit* carefully assessed). The traditional "decide, announce and defend" decision-making line has shifted to "engage, interact and co-operate" processes. These new approaches entail the provision of information to the public and involve communication and dialogue, as well as negotiations between various stakeholders, including the public and local communities.

Nuclear energy and waste management facilities in particular are clear examples of this. Involving the public in the decision process, instilling trust and attracting the interest, engagement and commitment of communities have increasingly assumed paramount importance in the development and siting of waste management facilities.

Public consultation and partnerships are both forms of public involvement entailing communication and dialogue as well as negotiations between various stakeholders, including the public and local communities. Both approaches also require the provision of necessary resources to community groups. Partnership arrangements seek to ensure both fairness (e.g. inclusiveness) and competence (informed decision making) and are also helpful in working out compensation and development opportunities (NEA, 2010).

Public involvement is favoured by stepwise and "adaptive staging" approaches in decision making (as also discussed in Section 2.3.2), in particular for long-term projects such as waste disposal facilities. Making a "decision" no longer implies the state opting for a complete and definitive package solution. By applying these approaches, the development of a project is undertaken in steps or stages during which the public, and in particular the most affected local public, are involved in the planning process (NEA, 2004a). Local and regional support is likely to be favoured by a voluntary siting process in which the consent of host communities is sought from the outset but can change within a certain period of time or under certain circumstances (NEA, 2004a, b). In this respect, public involvement goes beyond the information exchange, towards communication between different stakeholders. Such partnerships have been or are being set up in an increasing number of countries such as in Canada or in the United Kingdom, as well as:

- in the United States, where the new strategy embraces this concept (DOE, 2013);
- in Belgium, where local partnerships have influenced the process and affected the design of a disposal facility for LLW and ILW-SL;
- in Finland, where local partnerships between the utilities and the hosting communities are formed as a means to inform the public;

12. See NEA (2011a) and NEA (2011b) for details.

- in Spain, where a partnership approach has been used in the context of the siting process in order to find voluntary sites for nuclear facilities;
- in Sweden, where public consultation is an important component in the environmental impact assessment process and local authorities can get funding for their work from the Nuclear Waste Fund.

Due to the long-term nature of processes for siting and the lifetime of nuclear waste facilities, related stepwise decisions require creating and continuously maintaining confidence and acceptance of the public. Good examples are those of Finland and Sweden, where local stakeholders have high trust in implementers and regulators; this has proved vital in progressing nuclear waste management issues.

Important factors related to public involvement and public confidence are transparency and openness. These entail the provision of information at each step in the decision-making process before taking actions, in a fashion which is as far as possible understandable and comprehensible by the majority of the stakeholders. As a result, dialogue may be enhanced and opportunities given to people to get answers to questions that may arise during the process. Transparency establishes an environment of trust and partnership.

In the dialogue and negotiation, sociopolitical issues often are as important as technical matters. For instance:

- In the Republic of Korea, a substantial programme for compensation and local benefits has been important for the siting of an LLW repository.
- In Sweden, as a result of negotiations between different stakeholders, a "value-added programme" has been developed which looks at the development of the regional economy whilst considering added functionality to the project.

Approaches of implementation

Formal implementation of public involvement is based on legal frameworks and procedures. Legal frameworks have an important role for a democratic process and help building confidence. Veto rights and public hearings are examples of formal implementation of public involvement in the context of decision making.

In the European context, public involvement is built into EU directives: for instance, the Waste Directive, the Århus Convention and Espoo Convention.

One of the main procedures for public involvement in large infrastructural projects is the environmental impact assessment[13] (EIA). The objective of the EIA procedure is to promote the assessment and consistent examination of environmental impacts in planning and decision making. Even though EIA itself is not a decision-making process, it produces information which serves as a basis for decision making and also provides a set of legally binding rules on the information flows that are part of the decision-making process. Another objective of the EIA is to increase the opportunities for citizens to get informed and to become involved in the planning of projects, expressing their opinions on specific projects, or on the EIA documentation and its comprehensiveness (e.g. in Finland). Through public involvement, interaction between those responsible for the plans and the parties involved in the EIA procedure is achieved, contributing to the recognition of the impacts, bringing in the knowledge of experts and the opinions of citizens, and reducing misunderstandings and conflicts that may be caused by lack of information.

13. In the European context, the EIA is based on the Council Directive (85/337/EEC) on the assessment of the effects of certain public and private projects on the environment, including for nuclear waste facilities.

Parallel to the legal procedures, informal engagement is also vital in the context of nuclear facilities. This may consist of iterative dialogue developed at the local level, as exemplified in the cases described below:

- In Finland, local offices help by promoting communication and creating exchange between decision makers and local inhabitants. Events and seminars are held for public audiences and companies, as well as briefing and discussions for residents. Within the EIA procedure, audit group meetings are organised to promote data flow and interaction, while theme interviews are instigated as a means for assessing social impact.

- At the local level, in Sweden, meetings in the municipalities have been most important to promote dialogue. Official notes and proceedings of these meetings are documented and made available on the SKB website.

- In the United States, consultation is conducted mainly through hearings.

- In France, the law requires public engagement and the creation of a *Commission Locale d'information* (CLI), which is responsible for providing information to the local community. At the local level, public debates are organised, moderated by a specific committee and followed by a public inquiry, requiring detailed information.

Roles of different stakeholders

In order to build trust and confidence and establish smooth and clear communication flows, it is important to identify the various stakeholders and their different roles in public involvement. Dialogue should be as inclusive as possible, encompassing implementers, all affected governmental institutions at the national, regional and local level, as well as civil society, both as non-governmental organisations (NGO) and resident citizen groups (ENEF, 2011). In general the implementer or the government are responsible for running formal consultations. These involve legal procedures. For instance, in Japan consultation is possible almost only when a law is set up. Following the EIA legal procedure, the public should be informed and consulted on the project.

The implementers or utilities are responsible for the majority of the costs (e.g. in Finland) that may arise, typically when public hearings and other meetings with public are arranged.

The role of government organisations is also essential especially in the context of siting a nuclear facility (e.g. in Spain). In some NEA member countries, it has been accepted that the stakeholder dialogue is to be engaged at a national level, even if the decision at stake only affects, directly, a specific region. This seems to be particularly important if the facility is central to a specific energy policy or determines future developments in the energy sector. In Canada for example, a two-year nationwide campaign has been initiated to involve stakeholders in the definition of a national disposal policy.

Although the level of engagement and involvement of the regulators in the communication process vary from country to country, they have an important role, not only in mandated issues such as licensing and accident management, but also as a source of advice to the public on safety and risks.

Local communities can be regarded as partners and watchdogs. For instance, in Finland the municipalities have organised public events together with the safety authority to share information and to discuss the siting of nuclear facilities. Other different local stakeholders have organised seminars for companies interested in the opportunities offered by the project.

The role of NGOs differs across countries. In some countries, NGOs may not want to participate at all, while for instance in Sweden NGOs get financial assistance to participate in the site selection process.

2.3.4. Financing

National legislation, including Acts of Parliament, Decrees, or Directives, has been stipulated, which generally sets responsibilities and legal ownerships (discussed in Section 2.2.3) for the management of HLW and SNF, and which provides the authority for the related funds to be created and preserved. In line with the underlying ethical principles and international requirements, national legislation lays out the terms for securing adequate financial means. Legal requirements are also necessary to suitably manage the funds and to protect them against misuse. In general, responsibility for funding the management and disposal of SNF and radioactive waste lies with the owners of the NPPs, as radwaste generators bear all costs. As described in Section 2.2.3, in most countries waste management organisations have been established to discharge the liabilities.

The most common mechanism adopted for the accrual of funds is by raising a levy per kWh of nuclear electricity (NEA, 2010). In some cases, however, rather than setting up explicit levies on the electricity produced, waste producers can pay lump-sums or proportionally to the volumes of SNF/HLW produced, as it is the case of the Republic of Korea and in Belgium. The payments of fees and levies are accumulated in internal or external funds.

There is no harmonised, global approach adopted across countries to accounting for the funds. In most countries a segregated fund is established that is often administered by a third-party body; this approach favours transparency, insolvency protection and confidence. Effective ring-fencing and timely availability of funds are key attributes for the establishment of a functioning funding system. In the United States, a dedicated fee was established in the 1982 Nuclear Waste Policy Act (NWPA), to provide a stable funding source for nuclear waste management. However, the discretionary treatment given through various budgetary acts on the part of Congress and previous administrations has made access to the funds unreliable (BRC, 2012). In many countries that have established funds, the government itself (e.g. in the Czech Republic, or in the Netherlands where the money is stored in an account at the Ministry of Finance and guaranteed by the state), or a high-level organisation within the government is designated as the financial resource management organisation. In Japan a non-profit, third-party body designated by the Minister performs this function and in Spain the implementing organisation (state owned) manages the funds. In a few cases (as in France and Germany) financial resources are retained internally by the waste generators, who are responsible for their management and the determination of the annual amount to be deposited. In general, regardless of where financial resources are retained, the state exert a role of oversight and control on their management, e.g. through the development of criteria or guidelines and the assessment of fund adequacy and security. For instance, in France waste producers are required, by law, to follow rules for the prudent financial management of their segregated fund, which is assessed by the state.

Usually, the funds are statutorily managed in a low-risk manner (e.g. by depositing them in the national account, investing them in government bonds or following a financing strategy established by a designated body). Finland and Belgium have a unique system by which the waste generators (nuclear power plant operators) may borrow back up to 75% of the accumulated funds. In Finland full securities are required.

Appendix 4 summarises the financial arrangements adopted by different countries, highlighting some of their key features.

Any efficient funding provision needs to be based upon a thorough understanding of the liability inventories and their accurate cost estimates.

Back-end cost estimates

Estimates of the back-end costs are challenging as they have to take into account very long time schedules and the development of new technologies which are sometimes needed. Nevertheless most countries attempt to calculate the back-end costs as a basis for the assessment of funding needs. Back-end costs depend strongly on factors that are country specific or even site specific: national policies and the availability of infrastructure, different physical and technical conditions (e.g. different host rocks), individual national regulations (e.g. in the radwaste classification), economic conditions and the different itemisation and inclusion of costs. They are thus very difficult to compare across countries. Table 2.4 provides an overview of different cost elements included in the cost estimates which support the requirements for funding provisions for several NEA member countries.

Consideration is being given at the European level to promoting harmonisation, i.e. through a possible development of an "International Structure for Waste Repository Costing" as a parallel analogue to the "International Structure for Decommissioning Costing" (ISDC) for nuclear installations, recently generated through a joint IAEA/EC/NEA undertaking which proposes a standard itemisation of decommissioning costs.

Typically costs related to DGR implementation are spread out over almost a century. An example of time profile of costs, estimated over the entire DGR project cycle and disaggregated in individual components, is reported in Figure 2.2 for one of the cases[14] recently assessed in Japan by the Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc. on the direct disposal option, under the Japan Atomic Energy Commission (JAEC, 2011).

Funding can cover different costs in different countries. Notably, in some countries an overall fund is set up which also includes decommissioning costs, while in other countries decommissioning is funded through separate means (see also Appendix 4).

As most expenses related to long-term waste management, and in particular to its permanent disposal, can incur long after operations of an NPP have been discontinued and generating income stopped, such costs constitute a future financial liability. Provisions built up during operations to cover such liabilities, are often to be spent over a long, sometimes very long, period of time. In this respect regulated markets are more attractive for fund accrual than liberalised markets.

In economic and financial terms a sum received or spent today is not strictly equivalent to or comparable with a sum to be received or spent in the future, hence future values of assets or liabilities have to be converted into present values through discounting. Thus, the estimate of future costs is only one component in the calculation of the necessary funding. The other important factors are the scheduling of immediate and future expenditures, the remaining operational time over which fees are to be levied, and, most importantly, the real rate of return of the funded money. Inflation and performance of the funds have a strong influence on the fees and are key to ensuring the adequacy of financial arrangements and their compatibility with the timetable for liability management and related costs.

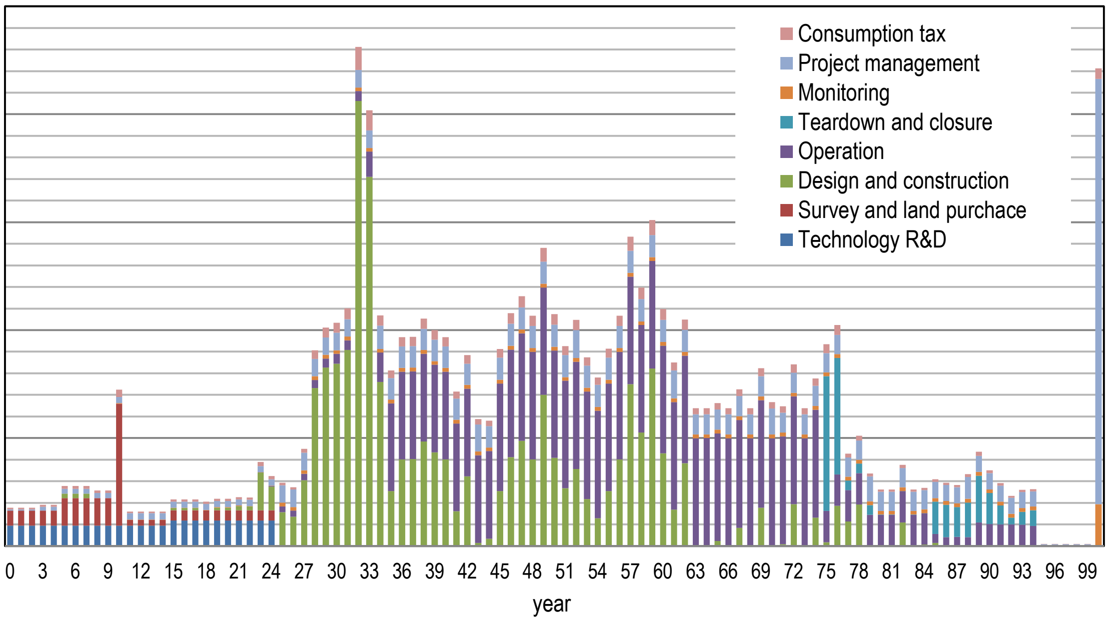
14. Because of the dependency of final disposal costs on the rock types and depth settings, different cases for a soft rock system (two different layouts) and hard rock systems have been estimated. Those reported in Figure 2.2 represent the costs estimated for a soft rock system (vertical layout, with two SNF elements per canister).

Table 2.4: Cost elements included in the cost estimates which support the requirements for funding provisions in NEA countries

	Belgium	Canada	Czech Rep.	France	Finland	Japan[1]	Korea, (Rep. of)	Netherlands	Spain	Sweden	Switzerland	United States
Reprocessing	√	N/A	N/A	Separate fund	N/A	Separate fund	N/A	√	√	N/A	√	
Siting and pre-construction	√	√	√	√	√	√	√	√	√	√	√	√
Transportation	√	√		√	√	√	√	√	√	√	√	√
Reception charges				√					√		√	√
Encapsulation	√	√	√	√	√	√	√	√	√	√	√	√
Final disposal	√	√	√	√	√	√	√	√	√	√	√	√
Interim storage	√			√	√	√	√	√	√	√	√[2]	√
On-site SNF storage	√			√	After NPP operation				√[3]		√	
Research and develop.		√		Partially	√	√	√		√	√	√	
Admin.				√	√	√	√		√	√	√	
Decommissioning[4]				[5]	√	√			√	√		√
Uncertainty margins[6]	√				√	√				√		
Others	Authority follow-up			- Licensing - Taxes	- Regulatory costs - Real estate taxes	- Consumption tax - Monitoring		Disposal of all other radwaste to be collected up until ~100 years from now	- Licensing - Taxes	- Licensing - Public involvement	- Authorisation and control by authorities - Monitoring and observation - Insurance	
Other waste			LILW[7]	LILW	LILW				VLLW, LILW	VLLW, LILW		
Legacy							√					

1. Source: JAEC, 2011.
2. Costs include the construction and operation of a central interim storage and the pool storage for the NPP in Gosgen.
3. In the case of "additional capacity".
4. Here, decommissioning does not refer to decommissioning costs of back-end facilities but to NPP decommissioning – i.e. if decommissioning is included in this cost estimate table, cost calculations include NPP decommissioning (and one fund is set to cover costs for SNF/HLW management and NPP decommissioning).
5. Includes some waste from NPP decommissioning.
6. Most countries include uncertainty margins in one way or another. In some countries (highlighted here) margins are mentioned explicitly, while in other cases they are implicit in the costs.
7. Charges for waste reception or transport of LILW. N/A = not applicable.

Figure 2.2: Example of time profile for costs estimated over the entire DGR project cycle



Note: The presumed schedule of operations considered in the assessment entails: 1 year for the selection of the executing body, 10 years for the selection of potential sites, 15 years for the survey of identified potential sites and demonstration of disposal technologies, 10 years for construction, 40 years of operation and spent fuel acceptance, ~20 years for dismantling of facilities and closure of site (up to the 95th year), 300 years of post-closure site management, the costs of this phase are reported cumulatively in the graph at 100th year.

Source: Derived from JAEC, 2011.

In particular, the definition of the real discount rate used in cost estimates, often regulated by national legislation, is generally based on hypotheses, e.g. on inflation and expected yields over time, which, given the long-term economic uncertainties, carry an arbitrary component in the evaluations. A considerable part of the specific costs in provision calculation are linked to sectors (e.g. civil engineering) which are typically affected by inflation indices whose values and rates of increase are greater than those of average inflation. Methods and assumptions, notably in the selection of the discount rate, used for discounting gross charges should be carefully considered, given the non-negligible impact that discounting has in the calculation of provisions. Different countries apply different real rates of return, ranging from zero to 5%. In Sweden, a different real discount rate is used according to the period concerned (in the latest calculations the real rate of return was assumed to increase from 0 to 2% over a ten-year period, taking the present economic situation into account, and then stay constant to 2.5% in the longer time perspective).

Any increase or decrease in the real discount rate produces a change in the discounted provision and any matching asset. This change would apply even if the estimates remain unchanged, i.e. at a constant gross value. In particular, a reduction in the rate used entails an increase in the provision or an increase in the period of accrual (*Cour des Comptes*, 2012). The latter, however, is not flexible in general, given that the accrual period is often linked to that of the NPP generating income and that cash outflows cannot always be deferred. This is particularly relevant in the current financial climate, where risk free investments yield much reduced real returns, relative to those available when earlier disposal funding schemes were established. This means, at a practical level, that for a given magnitude of back-end costs, a funding programme will need to provide for increased contributions (than when funds relied on risk-free returns in excess of 5%).

For the French case, sensitivity of provisions to discount rate variation is highlighted in Table 2.5 (*Cour des Comptes*, 2012). A reduction of 0.5% in the discount rate results in an increase in discounted nuclear provisions of almost 10%. Naturally, the variation impact is greatest for provisions with a long maturity date.

Table 2.5: Sensitivity of provisions to discount rate variation: impact based on 2010 provisions calculated with a rate of 5%

Discount rate	3%	3.5%	4%	4.25%	4.50%	4.75%	5%	5.25%	5.5%
EDF	15 313	10 000*	5 936	4 300*	2 782	1 312	0	-1 206	-2 349
AREVA	2 000**	1 500**	1 059	761	491	243	0	-217	-420
CEA	1 198	821	507	368	237	115	0	-108	-211
Variation (EUR millions)	+18 511	+12 511	+7 502	+5 429	+3 510	1 670	0	-1 531	-2 980

* *Cour des Comptes* estimates.

** AREVA estimates.

Source: Responses to the *Cour des Comptes* (2012) by EDF, AREVA and CEA.

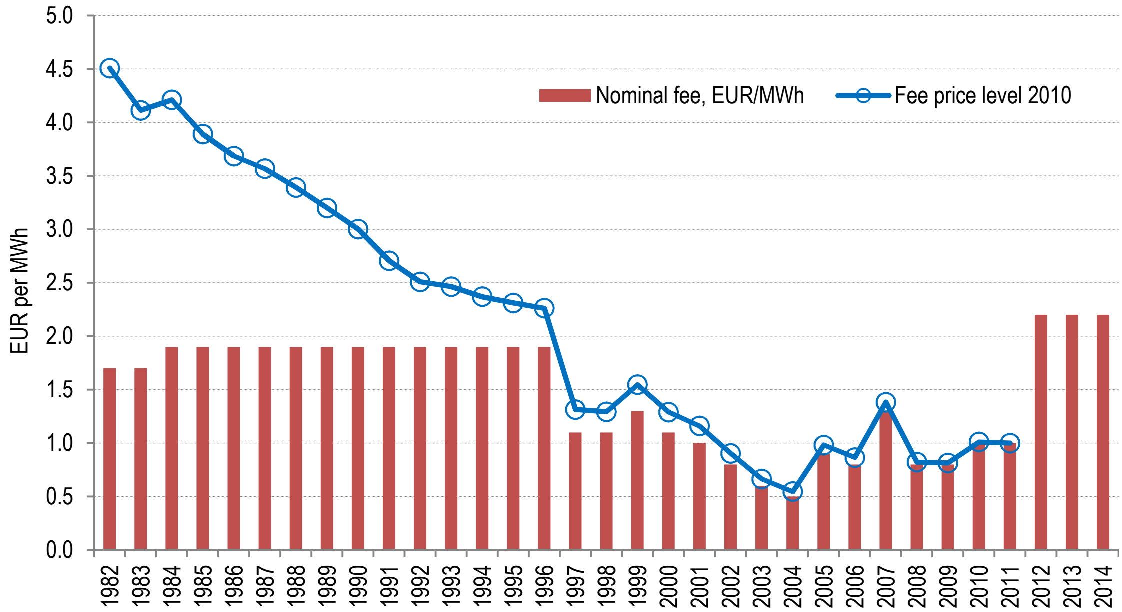
The impact of the rate of return applied for net present value estimations of future storage and disposal costs is considered further in Chapter 3.

As discussed in later sections, cost estimates of liabilities are generally affected by considerable uncertainties and are susceptible to changes. Most countries incorporate uncertainty margins in their cost estimates, in one way or another. In some countries (as indicated in Table 2.4) margins are mentioned explicitly in the cost assessments, while in other cases they are implicitly integrated in the cost items. Various approaches are adopted for the calculation and inclusion of contingencies: flat percentage margin on all figures, as set by historical rules; margins for technological and project risks depending on the level of planning and the knowledge of technologies used (e.g. EPRI [Electric Power Research Institute] margins); assessment based on expert opinions and derived from discrepancies between cost estimations and technical uncertainties; or even detailed risk analyses, such as Monte-Carlo simulations, sometimes including macroeconomic trends.

Indeed, as programmes advance, greater knowledge can be acquired on the actual costs, allowing stepwise refinements of projections. Cost estimates can thus evolve over time, ideally gaining in precision as implementation gets closer. In Switzerland, for example, the results of the 2011 estimate of the costs for waste management (Swissnuclear, 2011) show an increase of 10% compared to the 2006 estimates. According to Swissnuclear (2011), this difference does not reflect changes in cost methodologies (which are unchanged) or inaccuracies in the general evaluation, but can be ascribed, by and large, to an increase in the estimated costs of deep geological repository, as new insight and experience have been gained in various projects of construction of tunnels and nuclear facilities. The change also reflects the enforcement of more stringent requirements in nuclear construction observed in recent years (Swissnuclear, 2011).

The projected future electricity generation and the expected return of funded money are affected by uncertainties too and will vary over time. This will influence how the setting of the fee for the accrual of the corresponding funds develops in time. An example of the time evolution of fees is reported in Figure 2.3 for Sweden. The graph shows progressive adjustments applied to the fee since its inception. Initial values covered substantial levels of uncertainties, which could be gradually reduced as more accurate knowledge of costs has been gained through further advancements of the programme (explaining the general decreasing trend observed between ~1997 and 2009). The recent increases are mostly attributable to an initial underestimation of soft costs and particularly those related to increasing regulatory requirements and administration, but also to a lower expectation of future real rate of return of the funded money.

Figure 2.3: Time development of fees in Sweden



It is therefore essential, given the different uncertainties, that cost assessments are periodically reviewed and the status and performance of provisions verified, in order to ensure that the accrual of funds and their expected growth are on target, reflecting current best knowledge of all technical and financial aspects, and including actual developments in the country economy. In most countries such reviews are undertaken regularly, with typical frequencies varying from once a year to once every five years. In general, mechanisms are in place to allow required fee adjustments (e.g. to redress increasing cost estimates or underperformance of the fund).

Together with the early formulation of a strategy and plan for the SNF/HLW including associated cost estimates, the continuous update of cost projections in light of the practical experience and knowledge accrued, as well as the regular control of financial provisions (with fees levied as required) represent, at present, the principal means to ensure fund sufficiency and to address prospective deficits in time. Some funding systems contain further inbuilt features to minimise risks: as described above, uncertainties about prices and costs are generally reasonably taken into account by raising the estimated liability. In Belgium, a special fund has been built to cover any contingent costs associated with failed producers. This fund is fed by an additional charge on all the waste producers.

In several countries nuclear operators are to provide securities and guarantees (e.g. in Sweden) against unforeseen developments. In the Finnish system, no discounting is used (Nuclear Energy Decree 87 §, 88 §). In Finland and Sweden, the waste management programme is proceeding to the operational phase while NPPs are still in operation, thus generating income to cover possible cost increases.

Nonetheless, available country information suggests that, in general, even in the most robust systems, if shortages were to arise for instance due to bankruptcy of the licence holder, there might remain financial responsibilities that would have to be taken by the state, directly or through state-owned WMOs (e.g. in the Netherlands and Spain). In Finland, to provide for unforeseen costs, the government can decide on an extra security of up to 10% of the total liability (Nuclear Energy Act 44 §) and in Sweden the present legislation gives the possibility for the state to charge an extra risk fee to cover this eventuality, but this has not been implemented at present. Some elements of individual country arrangements are reported in Table 2.6.

Table 2.6: Features of country systems to protect against shortfalls in funds

Country	General features	To what extent are utilities required to add to the funds in case these are insufficient?	Are there systems in place with securities in addition to payment into funds?	What happens if a power utility goes bankrupt and there remains a lack in the funding?
Belgium	In case funding is insufficient utilities are required to provide the difference at the time the discrepancy arises. However, while this could be feasible for decommissioning operations, for expenditures expected in the long-term future, it may not be possible.	A special fund has been built to cover any contingent costs associated with failed producers. This fund is fed by an additional charge on all the waste producers. The use of this fund is submitted for regular auditing by a special surveillance committee.	• Contractual guarantee: each of the main producers commits himself to paying the long-term fund the balance of the fixed costs attributable to his waste that has not yet been covered by tariff payments. • Back-loans to the facilities (up to 75%) are permitted. However, these are not against securities and there are no specific controls or accounting mechanisms in place.	• If a utility goes bankrupt and there is not sufficient money in the fund the state remains responsible. • Steps are being taken to improve the system, by amending the relevant legislation. • Work on a new law project is ongoing to firm up responsibilities of waste producers over time.
Canada	Waste owners in Canada have established segregated trust funds, pursuant to the Nuclear Fuel Waste Act, and financial guarantees to pay for the full lifecycle costs of managing the waste. Canadian legislation places the full responsibility on the owners of the waste (i.e. nuclear utilities). Should there be any shortfall in funding the waste owners would be entirely responsible for addressing it.			
Finland	• The system allows distribution of the liability over 25 years of plant operations against full securities if a considerable part of the liability consists of fixed costs, like investments and D&D. • The funding of major increases in liability may be distributed over five years (following approval by the government). • At any given moment in time, the amount of liabilities which is not yet covered by the Fund has to be covered by securities supplied by the operators. (Nuclear Energy Act 44 §).		• Collateral securities to be provided by the operator prior to commencing waste generating operation; so that: • Total guarantees held by the state are equal to the difference between the assessed liability at the end of the calendar year and the Fund target (Nuclear Energy Act 44 §). • Operators can borrow money from the Fund against full securities (Nuclear Energy Act 52 §). • To provide for unforeseen costs, the government can decide on an extra security up to 10% of the total liability (Nuclear Energy Act 44 §). • Securities accepted are: - credit insurance provided by an insurance company; - direct liability guarantee provided by a Finnish savings bank; such as a real estate mortgage or - direct liability guarantee by a Finnish corporation as accepted by the government (Nuclear Energy Act 45 §).	In the case where a facility would unexpectedly stop its operation and the funds should be transferred to the state, the Fund has full right to require the operator to pay its loans back to the Fund or alternatively, to realise the securities (Government Decision 166/1988 7 §).
France	• France waste producers are responsible for radwaste management and for financing all the related costs. • Producers are required by the law to follow rules ensuring a prudent financial management of a segregated fund dedicated to finance such costs. Further, guarantees are provided by the holding company (state-owned). Should any deficit on the fund emerge (e.g. in eventuality of utility bankruptcy) the state would be liable. • Involvement of the French Ministry of energy (DGEC), the Safety authority (ASN) and the Financial Evaluation Commission (CNEF) in the verification of cost assessments.			

Table 2.6: Features of country systems to protect against shortfalls in funds *(continued)*

Country	General features	To what extent are utilities required to add to the funds in case these are insufficient?	Are there systems in place with securities in addition to payment into funds?	What happens if a power utility goes bankrupt and there remains a lack in the funding?
Netherlands	COVRA, the state owned WMO, can adjust the fee if the fund is judged inadequate.	In paying the fee, NPP operators and waste generators are discharged from further financial obligations.	No securities.	• Fee adjustments would have to be sustained by those companies that are still contributing to the fund. • In case of ultimate dearth of fund the WMO and, as a result, the state would be liable.
Spain	The Spanish legislation sets out that the state takes over the ownership of radwaste once this is definitively classified as a waste and disposed of. ENRESA, the WMO in Spain is state owned. Essentially the responsibility for addressing any inadequacy of the funds lies with the state.			
Switzerland	Contributions that operators must pay are based on a detailed estimate of costs for waste management. This is revised every five years and fees can be adjusted accordingly.	NPP owners are only relieved of their management responsibilities when the waste is placed in a deep repository and the financial resources required for the monitoring phase and the possible closure are ensured.	• The Nuclear Energy Act of 2003 (in force since 2005) regulates in detail the securities, obligations and additional contributions required from NPP operators. • If the contributions are not sufficient to cover the costs the contributors must reimburse the Fund the difference plus interest on the market.	• If the contributor cannot refund emerging shortfalls within the time set by the Federal Council, the difference must be covered by other contributors. • If the payment of the difference is not economically sustainable for these parties, the Federal Assembly decides whether, and to what extent, the federal government will contribute to the costs not covered.
Sweden	Swedish waste producers are responsible for the costs forever. Fees are adjusted every three years.	• A fee can be levied also after the cessation of power production to cover an unexpected lack in the fund (e.g. due to increasing cost estimates or less interest than expected). • This is at present the case for the Barsebäck reactors.	• NPP licence holders also have to provide securities to cover lack of funding due to early cessation of power production (before 40 years) or unexpected (but still realistic) cost increases. • Securities have to be backed up by parent companies, i.e. large power companies (Vattenfall, Eon, Fortum...).	• At first securities will be used but securities cannot cover every possible situation • Residual financial responsibility will have to be taken by the state. • Ongoing discussion to address this. • Current legislation allows the state to charge an extra risk fee to cover against this eventuality. • This has not been implemented.
United Kingdom[1]	In the new build context, the United Kingdom is offering – via its provision for "waste contracts" – to place a "cap" on unit ILW and SNF disposal cost. This way, prospective new nuclear operators should be provided with certainty over a maximum Waste Transfer Price they will be expected to pay the government for the provision of a waste disposal service. The cap will be set at a level where the government has a very high degree of confidence that it will not be exceeded (by the actual cost). The government and hence the taxpayer take on the risk of subsequent cost escalation, and a Risk Premium is included in the Waste Transfer Price to compensate for this. In addition, in setting a cap, the government takes the residual risk that the actual cost might exceed the cap and therefore an additional Risk Fee (over and above the Risk Premium) is incorporated in the Waste Transfer Price for this risk transfer.			
United States	In the event the Secretary determines that either insufficient or excess revenues are being collected, in order to recover the costs incurred by the federal government, an adjustment to the fee is proposed by the Secretary to ensure full cost recovery.	According to the U.S. Nuclear Waste Policy Act of 1982, in paying the fee [1 mills/kWh], NPP operators and waste generators have no further financial obligation.	No securities.	Fee adjustments would have to be sustained by those companies that are still contributing to the fund (even for those facilities that have shut down and ended their contributions).

Source: DECC, 2011a.

A somewhat different approach to funding SNF disposal has been taken in the United Kingdom in the new build context. As stipulated in its Funded Decommissioning Programme, operators of new nuclear power stations are required to make secure financial provision for their disposal liabilities during the operating lifetime of the power station. Through its provision for "waste contracts" the UK government is offering to place a "cap" on unit ILW and SNF disposal cost. This way, prospective new nuclear operators should be provided with certainty over a maximum Waste Transfer Price they will be expected to pay the government for the provision of a waste disposal service. The government and hence the taxpayer take on the risk of subsequent cost escalation, or the excess of actual costs over and above the costs considered in the definition of the cap (DECC, 2011a). Conversely, a risk premium and a separate risk fee are included in the Waste Transfer Price to compensate, respectively for the risks described above. This increases the operator's disposal costs in most scenarios but reduces operators' risks in financing the back end by removing what investors have often viewed as a potentially unlimited downside for these costs.

2.4. A brief summary for non-OECD countries[15]

Most of the nuclear power plants in the world (75%) are operating in countries that are members of the OECD/NEA. In mid-2012, however, more than 100 reactors were operating in 13 non-OECD countries, mainly in the Russian Federation (see footnote above), India, the People's Republic of China and Ukraine. In addition, several other non-OECD member countries are operating research reactors or are running other nuclear applications which will generate radioactive waste. Information about the plans for spent fuel and radioactive waste management in non-OECD member countries can be found in the country reports submitted under the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (IAEA, 1995).

All non-OECD member countries with nuclear power plants have programmes for the development of spent fuel and radioactive waste management, although at different levels of implementation. In the following section a short overview is given for the most important countries.

2.4.1. Russian Federation[16]

The policy for spent fuel management in the Russian Federation is based on the principle that SNF is not radioactive waste, but a valuable source for producing nuclear fuel components and a number of radioactive isotopes used in medicine, agriculture and industry. The national policy is based on the combination of controlled storage and reprocessing. At present most of the spent nuclear fuel is stored at NPPs and will subsequently be transferred to a centralised dry interim storage facility at Krasnoyarsk, where building of a reprocessing plant is planned to start between 2020 and 2025. It is envisaged that separated plutonium will be recycled in fast reactors. Some fuel from early NPPs (VVER-440 and BN-600) has already been reprocessed at Mayak together with fuel from nuclear powered icebreakers and research reactors. The study "*Management of Radioactive Waste and Spent Nuclear Fuel in the Russian Federation*", contracted by the OECD and issued in October 2012, reports, however, that the reprocessing of fuel from VVER-1000, research and RBMK reactors has presented a number of unresolved technical and financial issues, suggesting that for certain fuel types direct disposal may be necessary (Stoller, 2012). Prolonged interim storage, in particular, of these fuel types, may be an issue.

15. At the time when the expert group was established, the Russian Federation was not an NEA member country and the relevant country information obtained is not as comprehensive as for other NEA member countries.

16. The Third Russian Report to the Joint Convention, see IAEA (2012).

Development work is in progress for a HLW disposal facility. Extensive investigations for site exploration have been ongoing at the Mayak site since 1975 and at Krasnoyarsk since 1990 (Stoller, 2012). The latter is currently considered as the most suitable site and an underground research laboratory is planned for construction by 2021. According to the schedule elaborated in the recently enacted (July 2011) Federal Law on the Management of Radioactive Waste (No. 190-FL), the selection of a site for a DGR should be finalised between 2025 and 2030, depending on the results of relevant research and public discussion. Final implementation is expected beyond 2035. The adoption of this recent federal law should foster a more co-ordinated strategy for waste management at the federal level, which is crucial and urgent.

Disposal is considered to be a responsibility of the state, while the costs for spent fuel and radioactive waste management shall be covered by organisations producing the waste. A waste management organisation: the "National Operator" has been set up and a fund to finance the costs associated with the radioactive waste repositories has been established, in accordance with the new federal law. Further details on the requirements set out in this recent law are provided in Appendix 4. To implement such requirements, enforcement powers and functions have been conferred to "Rosatom" corporation as the governmental authority in the field of radioactive waste management.

The activities on waste management in the Russian Federation also need to consider the large amount of legacy waste from earlier military activities and from earlier power production (including all radioactive waste formed before the 2011 federal law was enacted) which are considered federal property.

2.4.2. India

India is performing a comprehensive nuclear power programme aiming at recycling plutonium in fast reactors and as thorium-plutonium fuel in advanced heavy water reactors (AHWR). For this purpose India has a few small scale reprocessing plants in operation and is planning to build some larger scale plants. HLW is stored at the reprocessing plants. A programme for developing a HLW disposal facility has started. The work is mainly funded through the state budget. Low- and intermediate-level waste is disposed in near-surface disposal facilities (Basu, 2010).

2.4.3. People's Republic of China

Spent fuel management policy in the People's Republic of China's is to implement the reprocessing of spent fuel. In a first step, the plutonium is planned to be recycled as MOX fuel in LWRs, while in the longer time frame recycling will take place in fast reactors. A pilot reprocessing plant is in operation and a larger facility is being planned. Until reprocessing, the spent fuel is stored in the reactor pools or in dry storage facilities on site. Studies on disposal of HLW are ongoing. A potential site for a rock laboratory has been chosen in Beishan in western China. A disposal facility is planned for mid-21st century. Low- and intermediate-level waste is disposed of in two near-surface facilities. Since 2010, a special fund within the state budget has been created for spent fuel and radioactive waste management (PRC, 2012).

2.4.4. Ukraine

Ukraine has previously sent its SNF to the Russian Federation for reprocessing. Plutonium and high-level waste is expected to be returned to Ukraine. This has not yet taken place. Facilities for interim storage of spent fuel have been developed, while discussions are ongoing about the future strategy for spent fuel management, as well as for the disposal of HLW, LILW, and the general organisation and funding of waste management activities. Importantly these need to encompass also the radioactive waste generated as result of the Chernobyl accident (SNRC, 2003).

2.4.5. Other countries

Other countries with only a few NPPs are still considering the strategy for spent fuel management. In most cases the fuel is stored at NPPs. Only Armenia and Bulgaria are shipping their fuel for reprocessing in the Russian Federation with a future return of HLW. Most countries have a programme for disposal of HLW and/or SNF. In the case of Argentina, this programme has been ongoing for more than 30 years, but in most other countries it is at a very early stage. Low- and intermediate-level waste is (or is planned to be) disposed in near-surface facilities. Funding systems have been developed in some but not all of these countries.

2.4.6. Countries with no nuclear power

Also countries that do not have nuclear power plants will in many cases have radioactive waste, mainly low- and intermediate-level, which will need disposal. Disposal facilities have so far only been built in a few of these countries.

2.5. Conclusions

Based on official data collected through a country questionnaire, an appraisal of country strategies and financial mechanisms for the long-term management of SNF and HLW has been undertaken in this chapter. Some conclusive remarks and findings emerging from the review are summarised in this section. Economic considerations are further developed in Chapter 3 together with high-level cost estimates and sensitivity analyses for theoretical models of the two industrial options – the once and twice-through fuel cycles – as well as a more advanced option with MOX and REPUOX recycling in LWRs (once) and continuous recycling of plutonium in fast reactors. The influence of other qualitative factors is discussed in Chapter 4.

2.5.1. National policies

- As regards SNF management, historically there has been a dichotomy in country policies, with countries adopting either the open fuel cycle or the partial recycling option.
- Countries that have opted for an open fuel cycle have built interim storage facilities and are pursuing studies for disposal, e.g. Finland and Sweden have applied for licence to build and operate repositories for spent fuel.
- In general, countries that have committed to reprocessing and recycling are developing fast reactors. These countries operate or have planned their own commercial reprocessing facilities (e.g. France, Japan and the Russian Federation). In these countries,[17] partial recycling is generally seen as an important intermediate stage towards the transition to full recycle in fast reactors.
- There are countries which have been holding off from developing firm or single strategies and have not formulated a final disposal policy. In a few cases, overcoming political and societal obstacles has proved to be a challenge in the establishment of a national policy for spent nuclear fuel, causing significant policy shifts over time.
- Longer-term interim storage is an increasingly adopted practice, either *de facto* due to extended times for the deployment of final repositories, or as a result of a considered strategy choice. The integral planning of longer-term interim storage of SNF can be seen as an important means to achieving greater flexibility for

17. With the exception of the United Kingdom, where a policy decision was made in 2012 not to reprocess fuel after 2018, including fuel from new reactors.

future fuel cycle decisions (MIT, 2011) and providing a safe transient measure during the transition stage of deployment of advanced systems and fuel cycles (which could still require up to some 100 years). However this raises questions of ensuring long-term integrity and safety of fuel elements.

- Any strategy for SNF management and any current and future fuel cycle options eventually require an operational repository for final disposal, be it national or regional.

2.5.2. DGR implementation

- Although no DGR for SNF and HLW has yet been built in the world, good progress has occurred in several countries. The most significant advances in disposal programmes have occurred in countries with a long-term continuity in policy positions, as it is the case in Finland, France and Sweden which are aiming for operational DGR facilities by 2020-2025.
- Increasingly organisations dedicated solely to implementing the SNF/waste management (WMOs) have been established or are being considered. WMOs hold various responsibilities, from the centralised collection of SNF/waste and the related processing capabilities to the final disposal; they can be either state organisations or owned by waste generators.
- Increased stakeholder engagement at the different stages and the move to partnerships with potential host communities, pursued through a stepwise approach adopted for DGR implementation, have resulted in improved public acceptance in some countries.

2.5.3. Funding and costing

- Assessments of the costs for managing spent fuel and radioactive waste is performed regularly in most countries. Given the long time periods included and the needs for technical developments, these calculations are challenging, they are affected by important uncertainties and are susceptible to changes; hence the importance of continuous monitoring, regular and frequent reassessments.
- Variability in costing is linked to a multiplicity of factors, often country specific, e.g. different physical and technical conditions (such as different host rocks), individual national regulations (e.g. in the radwaste classification), economic conditions and the different itemisation, boundary conditions and inclusion of costs.
- Comparisons between cost assessments in different countries are therefore very difficult.
- Much of the cost for managing SNF and HLW appears long after the electricity has been produced and revenue generation has stopped. Most countries have therefore set up a funding system based on internationally agreed principles (notably the "intergenerational equity" and the "user/polluter pays" principles) and in line with existing international instruments (i.e. the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management and the new Euratom Council Directive 2011/70).
- In alignment with the "user/polluter pays" principle, the waste producer is generally held responsible for accruing funds, typically through the revenues obtained from the electricity generated. However, it is always the state that is ultimately responsible for any residual liabilities. Country financial systems incorporate measures to safeguard the state in that respects; however such measures, while providing different degrees of protections, are unlikely to cover all risks.

- Most countries have established arrangements to cover the financial liabilities. However, there is considerable variability in the level of funds accumulated in different countries and there is no harmonised, global approach to funding arrangements and to developing the cost estimates upon which these are based.
- The estimate of future costs is only one component in the calculation of the necessary funding. The other important factors are the scheduling of immediate and future expenditure, the remaining operational time over which fees are to be levied, and most importantly the real rate of return of the money in the funds. The assumptions used in the selection of the discount rate, should thus be carefully considered.
- To ensure continued fund sufficiency and to address changes, cost estimates and funding requirements are updated at regular intervals, taking into account new technical knowledge and actual fund developments.
- Some funding systems contain further inbuilt features to minimise risks; for instance, in different countries securities and guarantees or risk premiums and fees may be requested to nuclear operators to protect against unforeseen developments.
- Of note is the new approach to funding SNF disposal taken in the UK new build context, whereby the UK government offers to place a "cap" on unit ILW and SNF disposal cost and charges a fee to the operator in return for this cost certainty. This increases the operator's disposal costs in most scenarios but represents an important shift towards the removal of what investors have often viewed as a potentially unlimited downside for back-end costs.
- Ring-fencing of funds is also required in order to ensure that funds are only used for the intended purpose. Although segregation of funds is generally pursued by most national legislations, this is not always true in every country and there have been cases where money collected for waste management has been employed for other uses.

References

Basu, S. (2010), "Indian strategy for management of spent nuclear fuel from nuclear power reactors", presentation at the IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors, Vienna, Austria.

BRC (2012), *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*, United States. Available at http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf.

CORA (2001), *Terugneembare berging, een begaanbaar pad?*, Ministry of Economic Affairs (*Commissie Opberging Radioactief Afval*), the Hague, the Netherlands. Available at www.kernenergieinnederland.nl/files/20010221-cora.pdf.

Cour des Comptes (2012), *The Costs of the Nuclear Power Sector – Thematic Public Report*, Cour des Comptes, Paris, France.

DECC (2011), *Management of the UK's Plutonium Stocks: A Consultation Response on the Long-term Management of UK-owned Separated Civil Plutonium*, Department of Energy and Climate Change, London, United Kingdom. Available at www.decc.gov.uk/assets/decc/Consultations/plutonium-stocks/3694-govt-resp-mgmt-of-uk-plutonium-stocks.pdf.

DECC (2011a), *Waste Transfer Pricing Methodology for the Disposal of Higher Activity Waste from New Nuclear Power Stations*, Department of Energy and Climate Change, London, United Kingdom. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/42629/3798-waste-transfer-pricing-methodology.pdf.

DOE (2013), *Strategy for the Management and Disposal of Used Nuclear Fuel and High-level Radioactive Waste*, Department of Energy, Washington DC, United States. Available at http://energy.gov/sites/prod/files/Strategy%20for%20the%20Management%20and%20Disposal%20of%20Used%20Nuclear%20Fuel%20and%20High%20Level%20Radioactive%20Waste.pdf.

ENEF (2011), *Good Practices Guide on Transparency for Nuclear Projects in the European Union*, Brussels, European Nuclear Energy Forum Working Group Transparency. Available at: http://ec.europa.eu/energy/nuclear/forum/transparency/doc/guide_on_good_practices.pdf.

EU (2006a), *Commission Recommendation of 24 October 2006 on the Management of Financial Resources for the Decommissioning of Nuclear Installations, Spent Fuel and Radioactive Waste* (2006/851/Euratom), European Union, Brussels, Belgium. Available at: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:330:0031:0035:EN:PDF.

EU (2006b), *Guide to the Commission Recommendation on the Management of Financial Resources for the Decommissioning of Nuclear Installations* (2006/851/Euratom). European Union, Brussels, Belgium. Available at: http://ec.europa.eu/energy/nuclear/decommissioning/doc/2010_guide_decommisioning.pdf.

EU (2011), *Council Directive 2011/70/Euratom of 19 July 2011 Establishing a Community Framework for the Responsible and Safe Management of Spent Fuel and Radioactive Waste*, European Union, Brussels, Belgium. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF.

Greneche, D., A. Chauvin and F. Laugier (2012), *Uranium : ressources, consommation et évolutions du marché*, Cycle du combustible nucléaire: de la mine à la fabrication du combustible, Editions Techniques de l'ingénieur, France.

GRWP (2006), *Sexto Plan General de Residuos Reaiactivos* (6th General Radioactive Waste Plan), Ministerio de Industria, Turismo y Comercio, Madrid, Spain. Available at www.enresa.es/files/multimedios/6PGRR_Espa_ol_Libro_versi_n_indexada.pdf.

IAEA (1995), *The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, IAEA safety principles, International Atomic Energy Agency, Vienna, Austria.

IAEA (2009), *Policies and Strategies for Radioactive Waste Management*, International Atomic Energy Agency, Vienna, Austria. Available at www-pub.iaea.org/MTCD/publications/PDF/Pub1396_web.pdf.

IAEA (2009a), *Status and Trends of Nuclear Technologies. Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)*, IAEA-TECDOC-1622, International Atomic Energy Agency, Vienna, Austria.

IAEA (2012), *National Report of the Russian Federation for the Second Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety*, International Atomic Energy Agency, Vienna, Austria. Available at: www.gosnadzor.ru/upload/fc/files/National%20report%20engl.pdf.

JAEC (2011), *Estimation of Nuclear Fuel Cycle Cost,* Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc., Edited by Atomic Energy Commission Bureau, Tokyo, Japan. Available (in Japanese only) at www.aec.go.jp/jicst/NC/tyoki/tyoki_hatsukaku.htm.

MIT (2011), *The Future of the Nuclear Fuel Cycle, An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, Massachusetts, United States.

NDA (2010), *Geological Disposal: Steps towards Implementation*, Nuclear Decommissioning Authority, Cumbria, United Kingdom. Available at www.nda.gov.uk/documents/upload/Geological-Disposal-Steps-Towards-Implementation-March-2010.pdf.

NDA (2012), *Oxide Fuels – Preferred Option*, Nuclear Decommissioning Authority, Cumbria, United Kingdom. Available at www.nda.gov.uk/documents/upload/Oxide-Fuels-Preferred-Options-June-2012.pdf.

NDA (2012a), *Frequently Asked Questions (FAQs) Related to Geological Disposal*, Nuclear Decommissioning Authority, Cumbria, United Kingdom. Available at www.nda.gov.uk/documents/upload/Frequently-Asked-Questions-related-to-Geological-Disposal-July-2012.pdf.

NEA (2001), *Role of Underground Laboratories in Nuclear Waste Disposal Programmes*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2001/nea 3142.pdf.

NEA (2003), "Topical Session on liabilities identification and long-term management at national level". Topical Session held during the 36th Meeting of the RWMC, OECD, Paris, France. Available at www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=NEA/RWM(2003)14&docLanguage=En.

NEA (2004), *Post-closure Safety Case for Geological Repositories: Nature and Purpose*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2004/nea 3679-closure.pdf.

NEA (2004a), *Stepwise Approach to Decision Making for Long-term Radioactive Waste Management – Experience, Issues and Guiding Principles*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2004/nea4429-stepwise.pdf.

NEA (2004b), *Learning and Adapting to Societal Requirements for Radioactive Waste Management – Key Findings and Experience of the Forum of Stakeholder Confidence*, OECD, Paris, France. Available at: www.oecd-nea.org/rwm/reports/2004/nea5296-societal.pdf.

NEA (2006), *Decommissioning Funding: Ethics, Implementation, Uncertainties*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2006/nea 5996-decommissioning.pdf.

NEA (2006a), *The Roles of Storage in the Management of Long-lived Radioactive Waste*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/ 2006/nea6043-storage.pdf.

NEA (2007), *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, Nuclear Energy Agency, OECD, Paris, France.

NEA (2007a), *Safety Cases for Deep Geological Disposal of Radioactive Waste: Where Do We Stand?*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2008/ne6319-safety.pdf.

NEA (2007b), *Management of Recyclable Fissile and Fertile Materials*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2008/ne6319-safety.pdf.

NEA (2008), *Timing of High-level Waste Disposal*, OECD, Paris, France.

NEA (2010), *Radioactive Waste in Perspective*, OECD, Paris, France.

NEA (2011), *Trends towards Sustainability in the Nuclear Fuel Cycle*, OECD, Paris, France.

NEA (2011a), Conference on Public Involvement in Siting of Nuclear Facilities (web page), OECD, Paris, France. www.oecd-nea.org/ndd/pubsiting/index.html.

NEA (2011b), "Actual Implementation of a Spent Nuclear Fuel Repository in Sweden: Seizing Opportunities", Synthesis of the FSC National Workshop and Community Visit, OECD, Paris, France.

NEA (2012), *Nuclear Energy Today*, OECD, Paris, France.

NNL (2012), *UK Nuclear Fission. Technology Roadmap. Preliminary Report*, National Nuclear Laboratory, United Kingdom.

Nuclear Energy Insider (2012), *Expert Review of Market Challenges in the Used Fuel Industry*, Nuclear Energy Insider, London, United Kingdom.

PRC (2012), "National report on sustainable development", the People's Republic of China prepared this National Report for the UN Conference on Sustainable Development held in Rio de Janeiro, Brazil, on 20-22 June 2012, Beijing, China. www.ctc-health.org.cn/file/The%20People%20Republic%20of%20China%20National%20Report%20on%20Sustainable%20Development-en.pdf.

RAND (2012), *Choosing a New Organization for Management and Disposition of Commercial and Defense High-Level Radioactive Materials*, RAND Corporation, Santa Monica, United States.

SNRC (2003), *Ukraine National Report – 2003*, prepared for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management of IAEA, Kiev, Ukraine. www.snrc.gov.ua/nuclear/doccatalog/document?id=52829.

Swissnuclear (2011), *Study on Costs 2011 – Summary Report*, Swissnuclear, Olten, Switzerland.

Stoller (2012), *Management of Radioactive Waste and Spent Nuclear Fuel in the Russian Federation* – report contracted by the OECD, Stoller Ingenieurtechnik GmbH, Dresden, Germany.

WNA (n.d.), Nuclear Power in France (web page), World Nuclear Association, London, United Kingdom. www.world-nuclear.org/info/inf40.html.

Chapter 3. Modelling the economics of back-end options

3.1. Discussion of key quantitative economic parameters and factors

3.1.1. Definitions of the total and specific costs of SNF management

The quantitative parameters characterising strategies for SNF management include the total cost of the implementation of a given strategy and the specific costs. The **total cost** is determined by the capital investment costs and operation and maintenance (O&M) costs of facilities required for the realisation of a given SNF management strategy. The **specific costs** e.g. cost of the SNF management per unit of electricity produced (or per unit of weight of SNF) allow estimations of the share of the back-end component in the electricity generation cost.

The exact evaluation of the costs of SNF management for a given country depend on many factors, in particular the inventory and characteristics of the accumulated SNF, the technologies available or accessible domestically and internationally, the tax regimes, the structure of the nuclear sector of the economy, availability of governmental subsidies, legal and regulatory aspects, risks, etc.

The general evaluation performed here uses simplified methodologies with a limited number of parameters to allow comparisons of different strategies.

The parameter most frequently used to quantify the costs of SNF management is the back-end component of the **levelised cost of electricity generation** (LCOE). The notion of LCOE is a simple and handy tool for the evaluation and comparison of the lifecycle cost of electricity generation with different technologies or within the same technology class (IEA/NEA, 2010). The total levelised cost of electricity generation at the plant level can be defined in the following way:

$$\mathrm{LCOE}=\frac{\sum_t \frac{\left(\mathrm{Investment}_t+\mathrm{O\&M}_t+\mathrm{Fuel}_t+\mathrm{Carbon}_t+\mathrm{Decommissioning}_t\right)}{(1+r)^t}}{\sum_t\left(\frac{\mathrm{Electricity}_t}{(1+r)^t}\right)} \qquad (3.1)$$

where the subscript "t" denotes the year in which the electricity production takes place or the expenses are made, and:

$\mathrm{Electricity}_t$:	The amount of electricity produced in the year "t";
r:	Annual discount rate;
$\mathrm{Investment}_t$:	Investment cost in the power plant, in the year "t";
$\mathrm{O\&M}_t$:	Operations and maintenance cost in the power plant, in the year "t";
Fuel_t:	Fuel costs in year "t" which include both front- and back-end costs;
Carbon_t:	Carbon cost in the year "t";
$\mathrm{Decommissioning}_t$:	Decommissioning cost in the year "t".

The LCOE could be seen as a ratio of two net present values: the numerator is the sum of discounted costs of construction, operation and decommissioning of the electricity generating plant and the denominator corresponds to the discounted cash-flow associated with the revenue obtained from selling electricity at constant price. Note that in this definition all electricity is sold at a constant price and the discount rate is assumed to be constant (see IEA/NEA [2010] for further details on the definition of the LCOE).

Although costs associated with the procurement of nuclear fuel and management of SNF are often measured in units of currency per unit of quantity of the fuel (e.g. USD/kgHM, USD per fuel assembly, etc.), the fuel cycle component in the levelised cost of electricity is expressed in units of currency per unit of energy produced (e.g. USD per MWh). Since the purpose of this chapter is to consider various fuel cycles having different fuel requirements and involving different waste streams, all the fuel cycle costs are expressed in units of currency per unit of energy produced. This allows comparisons between different fuel cycles.

The fuel cycle component $LCOE_{Total\ fuel\ cycle}$ of the LCOE for nuclear power plants is composed of the front-end cost (that includes the costs of uranium mining and enrichment and fuel fabrication) and the back-end cost that corresponds to the management of the SNF. The back-end fuel cycle component of the LCOE can be detailed as follows:

$$LCOE_{Back\ end}=\sum_{Back\text{-}end\ facilities,\ i}\left[\frac{\sum_{t=T_{i,\ start}-T_{ref}}^{T_{i,\ end}-T_{ref}}\left(\frac{Investment_{i,\ t}+O\&M_{i,\ t}+Transport_{i,\ t}+Decommissioning_{i,\ t}}{(1+r_i)^t}\right)}{\sum_{t=T_{NPP,start}-T_{ref}}^{T_{NPP,end}-T_{ref}}\left(\frac{Electricity_t}{(1+r_E)^t}\right)}\right] \quad (3.2)$$

where:

T_{ref}:	The reference year (all cash-flows are discounted to the reference year). For the calculation presented in the Section 3.3 T_{ref} is 2020;[1]
$T_{i,start}$:	Year in which begins the lifecycle of the facility i;
$T_{i,end}$:	Year in which ends the lifecycle of the facility i;
$T_{NPP,\ start}$:	Year in which NPPs start producing electricity;
$T_{NPP,\ end}$:	Year in which NPPs are permanently shut down and cease producing power;
r_E:	Annual discount rate for electricity cash flow;
r_i:	Annual discount rate for the cash-flows associated with construction and operation of the facility i;
$Electricity_t$:	The amount of electricity produced at NPPs in year “t”;
$Investment_t$:	Investments associated with the back end of fuel cycle, in year “t”;
$O\&M_t$:	Operations and maintenance costs at various steps of the fuel cycle, in year “t”;
$Transport_t$:	Transportation costs associated with the fuel cycle in year “t”;
$Decommissioning_t$:	Decommissioning of the back-end facilities, costs in year “t”;

1. In the strategies defined in Section 3.3 this roughly corresponds to the beginning of the operation of first back-end facilities (e.g. interim storage), see Figure 3.7-Figure 3.11.

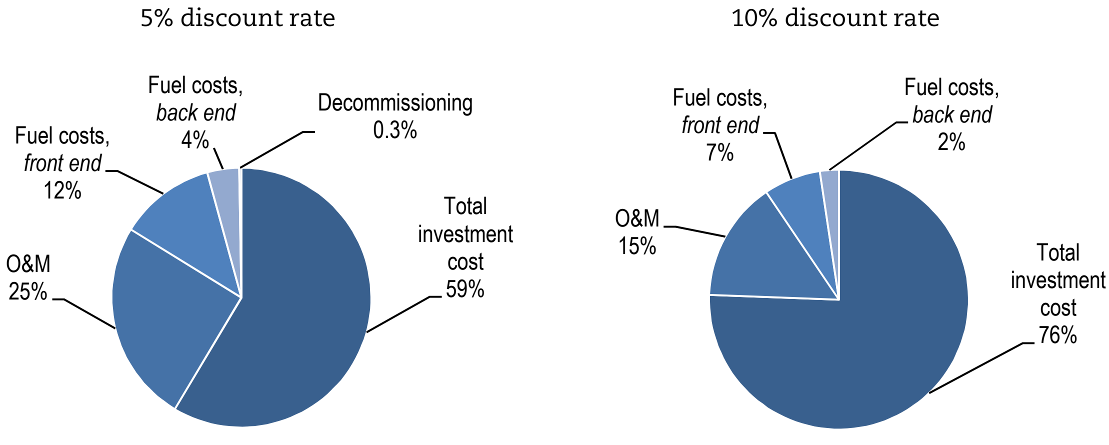
The list of back-end facilities in the formula above is determined by the strategy selected for the management of SNF and may include, for instance, installations for the interim storage of the SNF, its reprocessing, encapsulation and final disposal.

One should note that, generally speaking, the discount rates used for the calculation of the net present values associated with the construction of different back-end facilities (r_i) and the one corresponding to the electricity cash flow (r_E) may not be the same. However, for the sake of simplicity, it will be assumed in the Section 3.2 that all discount rates r_i and r_E are identical.

3.1.2. Factors influencing the fuel cycle cost

In this analysis total fuel costs are considered, including both the back-end and the front-end components, so that the use of recycled materials and the resulting savings in the requirements of fresh uranium can be taken into account for recycling options. The total fuel cycle cost, which includes both the part associated with procurement of the fresh nuclear fuel and the management of SNF, represents a relatively small fraction (about 10-16%, depending on the discount rate) of the total LCOE for NPPs (see examples in Figure 3.1). The front-end cost constitutes the main part of the total fuel cost. In this section the main factors influencing the front- and back-end components of the fuel cycle costs are briefly discussed.

Figure 3.1: Structure of nuclear electricity generation cost



Source: Median case from IEA/NEA (2010).

Prices of natural uranium and enrichment services

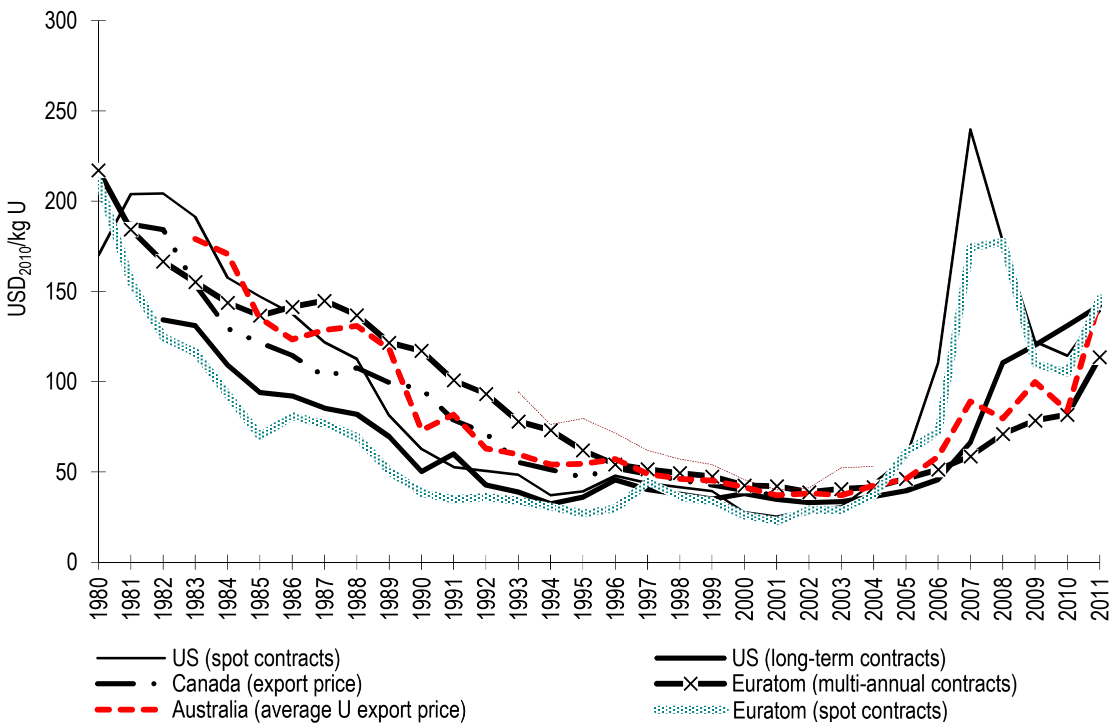
The factors influencing the uranium front end of the fuel cycle cost i.e. the cost of enriched uranium fuel elements include the price of natural uranium, conversion and enrichment services and the cost of fabrication of fresh nuclear fuel. The most important factors are the prices of natural uranium and enrichment services.

The evolution of the uranium prices[2] in 1980-2011 is provided in Figure 3.2. The prices of natural uranium (in constant USD_{2010}) were decreasing in the 1980s following an intensive exploration phase in the 1970s, improvement of fuel utilisation, and following the slowdown in new construction observed after the Three Mile Island and Chernobyl accidents. Also, an important factor keeping the uranium prices low in the 1990s is the

2. See NEA/IAEA (2011) for a detailed discussion of the data used in Figure 3.2.

secondary supply of enriched uranium from military stockpiles in the Russian Federation and the United States. Since the beginning of 2000s, the uranium price started to rise as a result of the prospective nuclear renaissance and new build in Asia. The uranium prices will probably not be as low as in the 1990s in the coming decades. Increasingly uranium will be mined in non-OECD/NEA member countries. It is envisioned that non-OECD/NEA member country demand for uranium resources will impact NEA member countries during the next decade and certainly during the following decades. Further rises in the price of uranium are expected along with an increase in price volatility, which will influence fuel cycle decisions in NEA member countries. It is notable that reactor vendors and fuel providers are securing their supplies of uranium by moving into uranium mining (NEA, 2011).

Figure 3.2: Evolution of natural uranium prices in 1980-2011



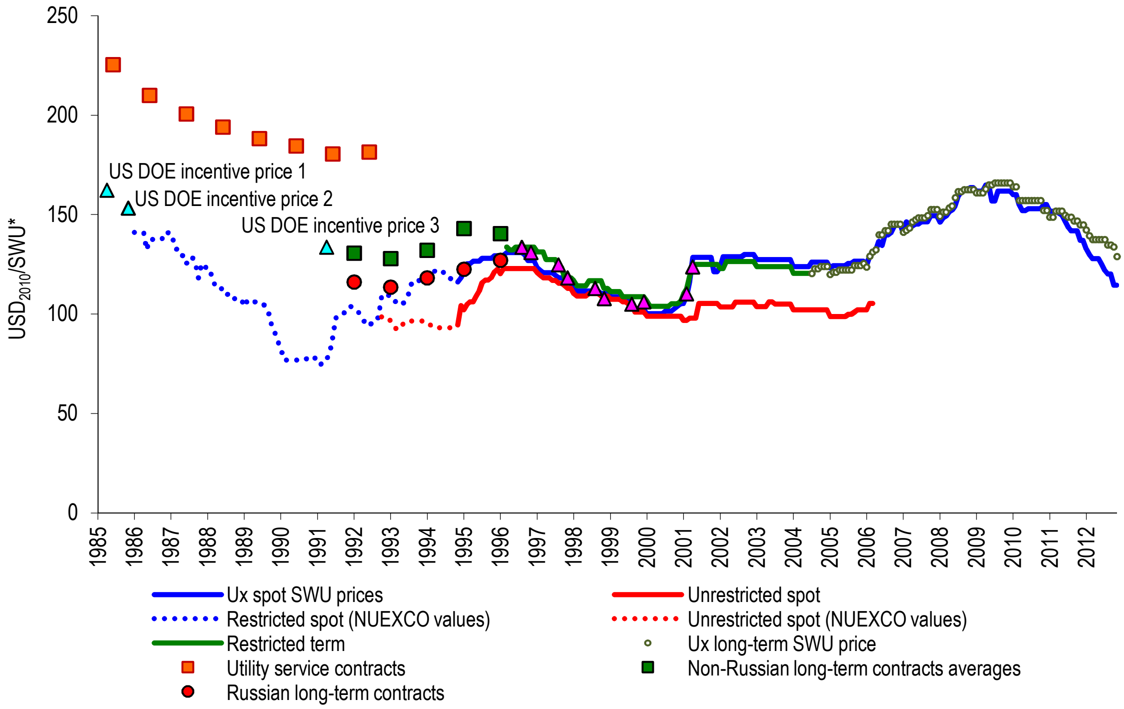
Note: The conversion from the current USD to USD_{2010} is performed using the gross domestic product (GDP) deflator.

Source: based on NEA/IAEA, 2011.

According to (NEA/IAEA, 2011), the total identified uranium resources (reasonably assured and inferred) represented, at the beginning of 2011, around 5.3 million tonnes of uranium metal (tU) in the <USD 130/kgU cost category. In the highest cost category (<USD 260/kgU), the total identified resources grew to about 7.1 million tU in 2011 (this represents an increase of 12.5% compared to 2009). The total undiscovered resources (prognosticated resources and speculative resources) were estimated in 2011 at about 10.4 million tU. It is suggested in (NEA/IAEA, 2011) that new resources can be identified with appropriate market signals since the favourable market conditions stimulate exploration and lead to the identification of additional resources of economic interest.

The price of enrichment constitutes another significant component of the cost of the fresh uranium fuel. The evolution of the separative work unit (SWU) price in 1985-2012 is given in Figure 3.3. In 2000, about half of the world's enrichment services was supplied by energy consuming gaseous diffusion enrichment plants. This technology is being progressively replaced by the centrifuges (consuming about 50 times less energy per SWU) that, in 2010, produced nearly two-thirds of enrichment services. In 2010 nuclear power plant requirements for uranium enrichment services were about 45 million SWU and projections show that annual world enrichment requirements should rise 23% to about 55 million SWU by 2020, and by a further 31%, to 70 million SWU, in 2030 (see Meade and Schwartz, 2011). The supply capability in 2010 was only slightly (by about 4%) exceeding the demand in enrichment services, but an approximate balance between demand and supply is forecasted for the long term. Although the spot prices for enrichment (per SWU) have recently decreased, it is unlikely that they will stay at low levels in the long term, because of ongoing growth of demand for enrichment services, the need to recover investment in new enrichment capacities replacing old gaseous diffusion plants and compensating the effect of the potential loss of the highly enriched uranium (HEU) down-blending programmes.

Figure 3.3: Evolution of prices for enrichment services (SWU) in 1985-2012



* The conversion from current to USD_{2010} was performed using the gross domestic product (GDP) deflator.

SWU = separative work unit; US DOE = US Department of Energy.

Source: Based on the data provided by the Ux Consulting Company, LLC (www.uxc.com).

Factors influencing the cost of the SNF management

The factors influencing the back-end component of the LCOE depend on the strategy adopted for the SNF management. Depending on the strategy the set of facilities required for its implementation can vary, along with the schedule of their deployment.

For the direct disposal this set of facilities includes the interim storage facility, the encapsulation facility, where the SNF fuel bundles are packaged and prepared for disposal, and a deep geological repository for final disposal. For fuel cycle strategies with reprocessing and recycling, the set of facilities is wider and includes a reprocessing plant, a MOX fuel fabrication plant, HLW vitrification plant, a waste conditioning plant, along with a final repository (for the nuclear waste), as for the once-through FC.

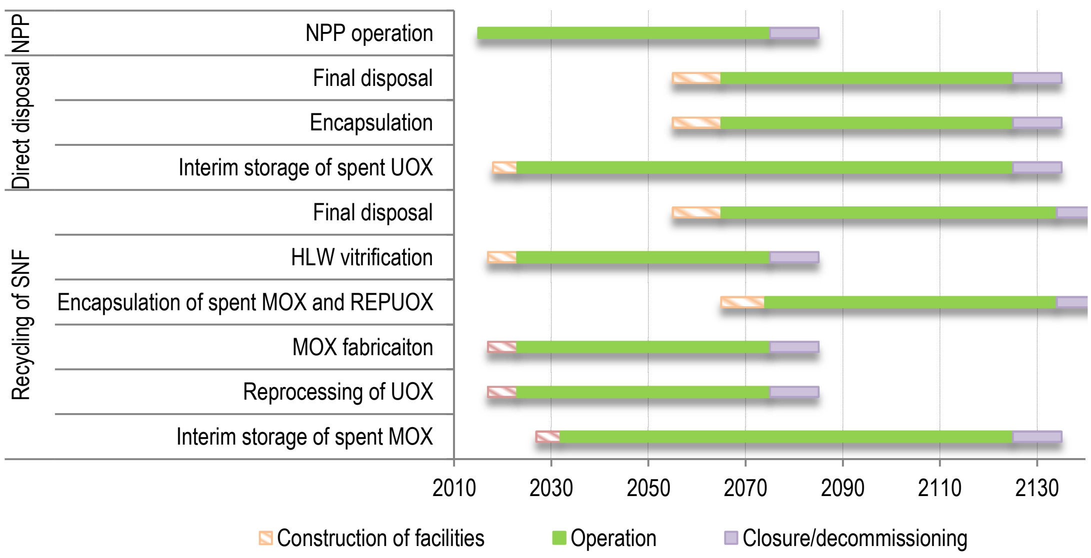
It should be noted that the strategy adopted for the management of the SNF can also affect the front-end cost, for instance, if the SNF is recycled, less freshly mined uranium is needed. The total fuel cost should be considered comparing the economics of SNF management strategies.

The costs associated with the realisation of the SNF management strategy will depend on:

- type, quantity and conditions of SNF;
- overnight investment costs and O&M costs of facilities required for the implementation of the SNF management strategy;
- total cost of financing its implementation;
- expected time profile of expenditures and financial arrangements for the strategy implementation.

The $LCOE_{Back\text{-}end}$ calculated using equation (3.2) is strongly dependent on the time profile of expenditures and the discount rate. The expenditures appearing far in the future (e.g. the deep geological repository) after the end of NPP electricity generation will have significantly lower weight in the $LCOE_{Back\text{-}end}$ than expenditures arising during electricity generation (e.g. reprocessing of the SNF), see Figure 3.4 for a theoretical example.

Figure 3.4: Examples of differences in time profiles for implementing direct disposal and partial recycling strategies, for NPPs operating between 2015 and 2075



3.2. High-level estimates of key cost parameters for near-term back-end strategies

One of the primary aims of this report is to assess the available knowledge from different countries on the costs of the various options for the long-term management of SNF and, to the extent possible, compare the cost estimates of different countries on a common basis. Since it is practically impossible to establish this common basis and directly compare the costs of SNF management in different countries,[3] it was decided by the

3. Because the types and quantities of the accumulated SNF, the regulatory and legal frameworks, the technologies involved and other factors differ significantly from one country to another.

expert group to perform generic case studies for idealised systems. As detailed in the sections below, the systems under consideration represent a theoretical vision of a nuclear programme, for instance nuclear reactors are assumed to be of the same type and producing SNF with identical characteristics; no accumulated SNF or legacy waste is considered. The main characteristics of a system is thus the size of the nuclear fleet, reflecting the fact that the economics of SNF management in a country with only one or a few nuclear power reactors would differ significantly from the case of a very large nuclear programme with tens of reactors. It is emphasised that the purpose of the proposed theoretical analysis is primarily illustrative. The economics of the fuel cycle management is obviously strongly affected by variations through the effectively implemented or contemplated strategies and their dynamics. Since most countries face specific challenges and have adopted strategies in between the three limit-cases scenarios, it will be necessary to assess in greater detail their economics.

Evaluations and a sensitivity analysis of costs associated with the management of SNF from LWRs were performed in the Greenfield approach[4] for the following strategies (it is acknowledged that the set of strategies and scenarios covered in this analysis is not exhaustive, as many different options could be considered and assessed in greater detail):

1. **direct disposal of SNF** (see Figure 3.6);
2. **partial recycling in LWRs**: Twice-through (REPUOX and MOX) and disposal of the spent MOX and spent REPUOX (see Figure 3.8);
3. **multiple Pu recycling with LWRs and FRs**: MOX and REPUOX recycling once in LWRs and multiple plutonium recycling in fast reactors (see Figure 3.10).

CANDU fuel cycles have not been assessed in the study. These FCs may have very different economic features, since front-end costs are reduced (as, e.g., no enrichment is required) and back-end costs may diverge substantially from those of LWR FCs (notably, recycling costs may be higher, due to the lower burn-up and subsequent larger amount of irradiated fuel to reprocess).

The analyses were conducted using a static model[5], with capital costs and O&M costs of different fuel cycle facilities (different for different systems) as input data. The primary aims of these evaluations were to perform:

- a generic comparison of costs of different strategies of SNF management;
- a sensitivity analysis of these costs to key input data (costs of different fuel cycle facilities, level of uranium prices, general economic conditions, etc.).

A calculation tool (an Excel spreadsheet) was developed within the project and input data provided by member country delegates were reviewed. The general framework of the model is presented in Section 3.2.1. Sections 3.2.2, 3.2.3 and 3.2.4 summarise the assumptions adopted for the three SNF management strategies listed above. In Section 3.2.5, the available economic data and additional assumptions on the capital and O&M costs of different back-end facilities are outlined and parameterisation undertaken with respect to capacity. Finally, Section 3.2.6 reports the results of the modelling and Section 3.2.7 presents the sensitivity analysis.

4. The “Greenfield” corresponds to a situation where only SNF from new NPPs is considered, and no accumulated waste is taken into account.
5. Static models (typically spreadsheets) produce costs that represent a “snapshot-in-time” equilibrium fuel cycle. Dynamic models (typically system dynamic models) also consider dynamic conditions such as start-up, ramp-down, end-of-life conditions, intermittent or long-term storage strategies, fuel cycle facility and reactor deployment scenarios.

3.2.1. General description of the model

As discussed in Section 3.1.1, the comparison of economic parameters of different strategies for the SNF management requires the calculation of the *total* fuel cycle cost, including both the front-end and the back-end components. This allows taking into account the savings of fresh uranium through the use of recycled materials (reprocessed uranium and plutonium in the form of REPUOX and MOX fuel respectively), and evaluating the associated costs and revenues.

Structure of the model and input data

The general input data for the calculation of the total fuel cycle cost $LCOE_{Fuel\ cycle}$ (see Figure 3.5) include:

- **Size of the nuclear system**: Total and constant NPP generation (in TWh/year). Most of the case studies have been performed for systems of 25, 75, 400 and 800 TWh/year.
- **Discount rate**: In most cases, the levelised costs were calculated for 0% and 3% real discount rates. Low discount rates are preferred for long-term public benefits projects.[6] A sensitivity analysis with respect to the discount has been performed for a range of values 0-10%. It is important to stress that, for the sake of simplicity, the same discount rate was used for discounting all the cash flow associated with the construction and operation of all the back-end facilities and also for the electricity cash flow (see discussion in Section 3.1.1). The cash-flows have been discounted to the year T_{ref} 2020 (roughly corresponding to the start-up of the first back-end facilities, see Figures 3.7-3.11).
- **General fuel cycle characteristics**: Average enrichment, ^{235}U content in enrichment tails, average fuel burn-up of the fleet, average thermal efficiency of NPPs.
- **Cost assumptions for the (uranium) front end:** The prices of natural uranium, conversion and enrichment services. The reference case assumptions were derived from the historical price data (see Figure 3.2 and Figure 3.3 for natural uranium and enrichment services respectively) and are summarised in Table 3.1. The management of the excess depleted uranium is not discussed in this study, and the associated costs are assumed to be included in the front-end costs of natural uranium and enrichment.
- **Overnight investment cost and O&M costs for facilities** required for the implementation of the given SNF management strategy (see Section 3.1.1).
- **Transport costs** related to the back end of the nuclear fuel cycle (the costs associated with the transport costs of the uranium front end are assumed to be reflected in the prices of uranium).
- **Decommissioning costs** of the back-end facilities: For all back-end facilities, a decommissioning cost equal to 15% of the overnight investment cost is assumed, except for DGRs, for which closure costs were obtained from member countries' estimates (see Section 3.2.5). The decommissioning costs for nuclear reactors were not considered in the present analysis, since only the fuel cycle is discussed here.

6. For example, in the United States, in its Circular No. A-94, *Discount Rates to Be Used in Evaluating Time-Distributed Costs and Benefits* (Appendix C revised December 2012), the Office of Management and Budget currently requires that real discounts rates of 1.1% be used for 30-year (and longer) projects. See www.whitehouse.gov/omb/circulars_a094 for details.

Figure 3.5: General structure of the model

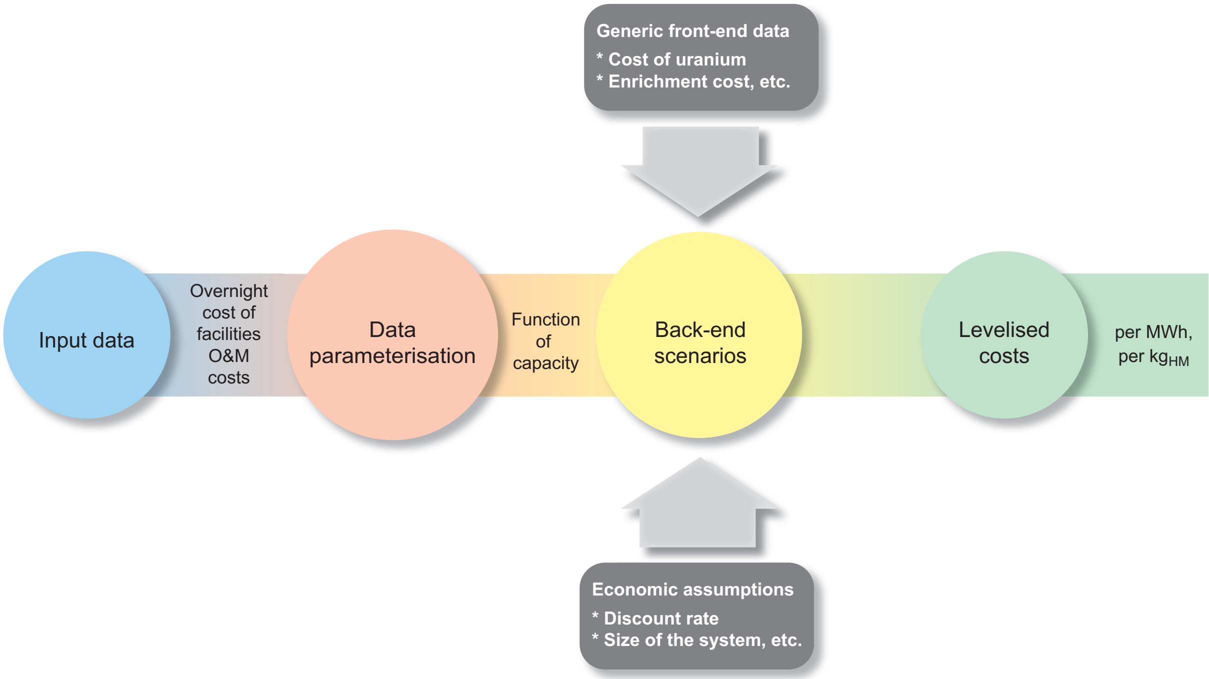


Table 3.1: Assumptions on the front end (for the reference case) in all three strategies (see also Section 3.1.2)

	Value	Unit
Natural uranium cost	130	USD per kgU
Conversion cost	9	USD per kgU
Enrichment cost	140	USD per SWU
Fuel fabrication cost for UOX and REPUOX	300	USD per kgU
Fuel enrichment (fresh UOX)	4.95%	Per cent
Additional enrichment for the REPUOX fuel*	0.15%	Per cent
Enrichment tailings	0.25%	Per cent
^{235}U content in the spent fuel	1.00%	Per cent

* Based on ORNL, 2007. Additional enrichment is needed because of the presence of neutron absorbing ^{236}U in the reprocessed uranium.

Using these input data, the back-end fuel cycle component of the LCOE can be calculated using Equation 3.2 (see Section 3.1.1). In calculating back-end costs for the recycling options, no specific credit is associated to recyclable materials, i.e. these are not attributed any explicit value. However, the deriving savings are taken into account indirectly, by reducing the requirements of fresh UOX. In this respect, the back-end costs are considered as all fuel cycle costs minus the UOX costs (costs of natural uranium and its subsequent conversion, enrichment and fuel fabrication costs).

In addition to the general data (e.g. discount rate, uranium front-end cost parameters, etc.) the overnight investment cost and O&M costs for the back-end facilities were parameterised as functions of capacity (e.g. tHM or tHM/year). The parameterisations are performed in three cost scenarios: low, reference and high reflecting, respectively, the lower bound of costs, the most likely value and the upper bound of the costs. The description of the above cost scenarios and their parameterisation is discussed in Section 3.2.5.

The key outputs of the model are:

- estimates of the net present cost of implementation of a given SNF management strategy;
- levelised fuel cycle costs (per MWh) in constant USD of the year 2010.

The uranium front-end cost calculations

The uranium front-end cost calculations of UOX and REPUOX were performed using the standard formulae (see NEA, 1994) that are summarised in Table 3.2. It is assumed that the front-end costs (of natural uranium, conversion and enrichment services) are constant in time. Since the electricity output and the cost are also assumed constant in time (see Section 3.1.1), one has:

$$LCOE_{Fuel\ cycle}=\frac{\sum_{t=1}^{T}\left(\frac{[UOX\ costs]_t}{(1+r)^t}\right)}{\sum_{t=1}^{T}\left(\frac{Electricity_t}{(1+r)^t}\right)}+LCOE_{Back\ end}=[UOX\ costs\ per\ MWh]+LCOE_{Back\ end}$$

Table 3.2: Uranium front-end calculations

[UOX costs]:	[UOX fuel weight] = $(1-x_{MOX})/(\eta\cdot BU\cdot 24/1000)$, *tU/TWh*
	x_{MOX} – fraction of MOX fuel,
	BU – average LWR fuel burn-up, *GWd/tHM*
	η – average NPP thermal conversion efficiency
	[Natural uranium weight] = $(e_{fuel} - e_{tail})/(e_{nat} - e_{tail})$·[UOX fuel weight - REPUOX fuel weight], *tU/TWh*
	e – enrichment,
	[Cost U_{nat}] = $Cost_{U3O8}$·[natural uranium weight], USD/TWh
	[Cost conversion] = $Cost_{conversion}$ [natural uranium weight], USD/TWh
	[Cost enrichment from natural uranium] = $N_{SWU}\cdot Cost_{SWU}$·[fresh UOX fuel weight], USD/TWh
	where $N_{SWU}= V(e_{fuel})-V(e_{nat})+(e_{fuel} - e_{nat})/(e_{nat} - e_{tail})\times(V(e_{tail})-V(e_{nat}))$, *SWU/kg$_{fuel}$*
	and $V(z) = (2z - 1)Log(z/(1 - z))$
	[Cost enrichment from reprocessed uranium] = $N_{SWU}\cdot Cost_{SWU}$·[REPUOX fuel weight], USD/TWh
	$N_{SWU}= V(e_{fuel})-V(e_{REPU})+(e_{fuel} - e_{REPU})/(e_{REPU} - e_{tail})\times(V(e_{tail})-V(e_{REPU}))$, *SWU/kg$_{fuel}$*
	[Cost fuel fabrication] = $C_{fuel\ fabrication}$·[UOX and REPUOX fuel weight], *USD/TWh*

Further assumptions for the uranium front end are reported in Sections 3.2.2 to 3.2.4 for the individual strategies considered and include:

- fuel fabrication costs for UOX and REPUOX fuel are assumed to the same;
- the specific, per SWU, enrichment costs for natural and reprocessed uranium are considered to be identical.

A sensitivity analysis is performed in this study with respect to the total UOX cost, as discussed in Section 3.2.7.

3.2.2. Direct disposal of SNF route

In the *direct disposal route* the SNF is stored, encapsulated and finally disposed in the deep geological repository (see Figure 3.6). In this idealised strategy, all the back-end facilities required for the management of the SNF produced by a fleet of LWR NPPs operating between 2015 and 2075 (see Figure 3.7) are assumed to be ready and operational exactly at the time when they are required.

Based on NEA (2006), the following parameters for the front end of the fuel cycle and LWRs were considered:

- the enrichment of the fresh UOX fuel e_{fuel} is 4.95%;
- the fuel burn-up is 60 GWd/tHM;
- the energy conversion efficiency of the LWR is 34%.

After irradiation in LWR reactors, the SNF is cooled at the reactor site for 7 years and then is transported to the interim storage facility where it is stored for 50 years. After this period, the SNF is transported to the encapsulation facility and finally disposed in the deep geological repository.

Figure 3.6: Direct disposal route

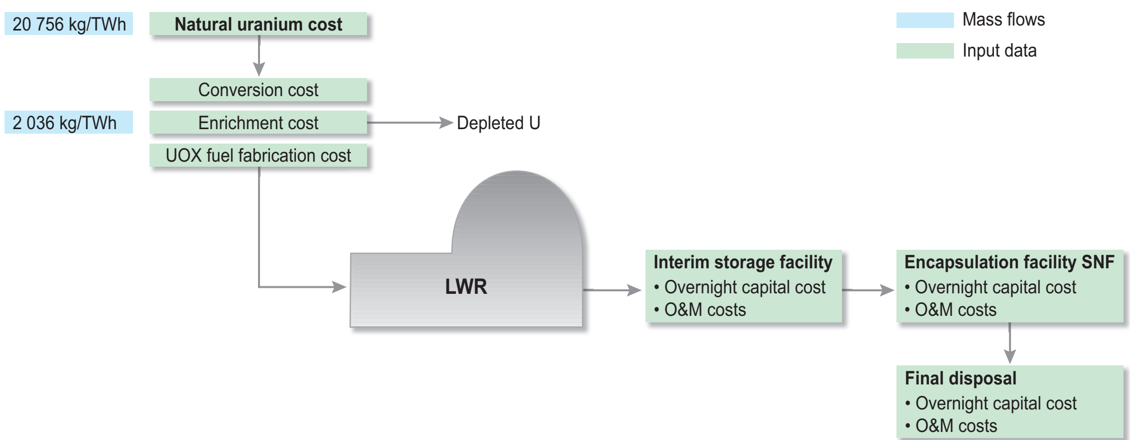
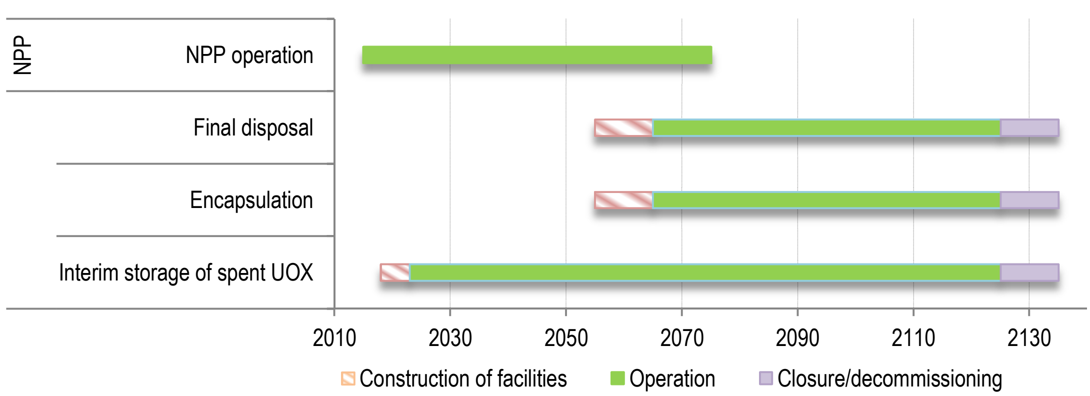


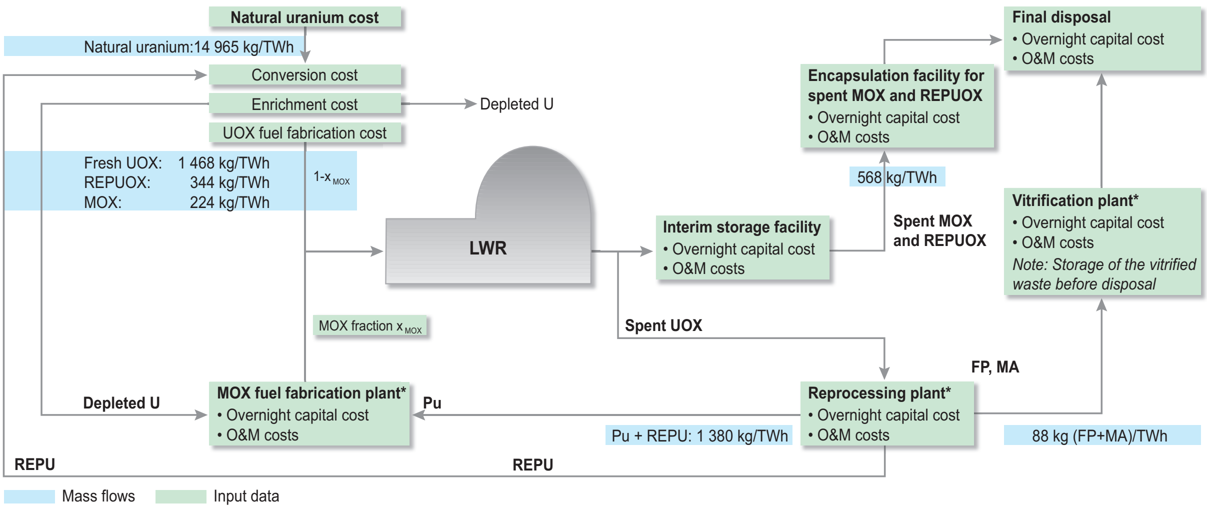
Figure 3.7: Construction and operational periods of facilities involved in the definition of direct disposal route



3.2.3. *Partial recycling in LWR route*

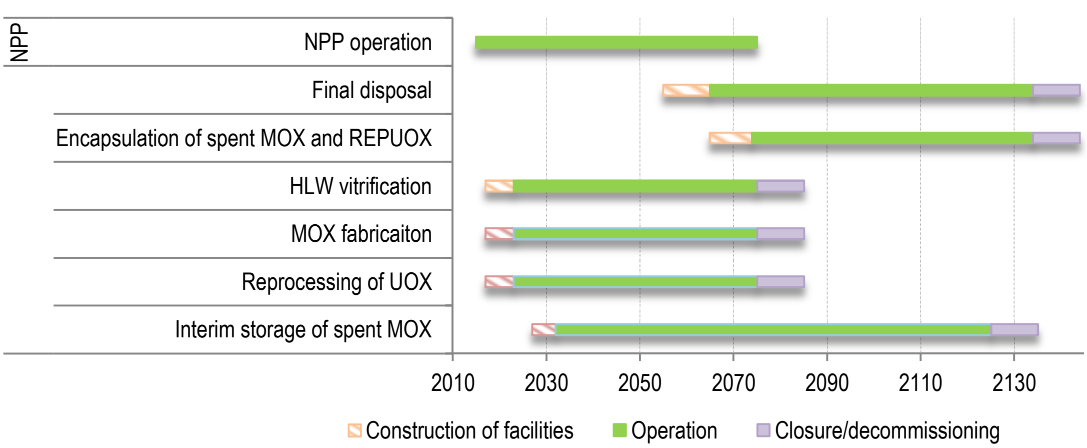
Contrary to the direct disposal route described in the Section 3.2.2, in the strategy of *partial recycling in LWRs* spent nuclear fuel is reused. In this strategy (summarised in Figure 3.8), the SNF is reprocessed, and the recovered fissile materials, plutonium and reprocessed uranium, are recycled once in the form of MOX and REPUOX fuel. Irradiated MOX and REPUOX fuel bundles are then stored in above ground facilities for 50 years prior to their final disposal in the deep geological repository. In this idealised strategy, all the back-end facilities required for the management of the SNF produced by a fleet of LWRs operating between 2015 and 2075 (see Figure 3.9) are assumed to be ready and operational exactly at the time and in the period when they are required.

Figure 3.8: Partial recycling in LWRs route with REPUOX and MOX recycling in LWRs



* In the model an integrated reprocessing plant has been considered, including reprocessing, MOX fabrication and HLW vitrification facilities.

Figure 3.9: Construction and operational periods of facilities involved in the definition of the partial recycling in LWRs strategy



The following assumptions for the route of partial recycling in LWRs are considered (based, to a large extent, on the *Scheme 1b "Conventional reprocessing fuel cycle"* covered in NEA, 2006):

- The enrichment of the fresh UOX fuel is 4.95%.
- The additional enrichment[7] for the REPUOX fuel is 0.15%.
- The UOX fuel burn-up is 60 GWd/tHM.
- The MOX fuel burn-up is 60 GWd/tHM. The MOX fuel is assumed to have the same energy efficiency as UOX fuel (per kgHM).
- The energy conversion efficiency of the LWR is assumed to be 34%.
- The UOX fuel is reprocessed after seven years of cooling in the pool at reactor site. The separated plutonium and reprocessed uranium are used to fabricate MOX and REPUOX fuel, which is recycled once in LWRs. LILW-LL streams generated during reprocessing are not considered in the calculations.
- No explicit credit is given for recycled fissile materials. The economic value of plutonium and recycled uranium is taken into account though the reduction in requirements of fresh UOX fuel.
- Reprocessed uranium is enriched and used to produce REPUOX fuel (the cost of additional enrichment for REPUOX is evaluated separately as defined above). The specific, per SWU, enrichment costs for natural and reprocessed uranium are considered to be identical, and the fissile value of REPUOX is assumed to be the same as the UOX.
- 11% of power is generated using MOX fuel bundles.
- FPs and MAs are vitrified and disposed after 50 years of cooling (at the vitrification plant).
- It is assumed that the separation and vitrification of FPs and MAs reduces by a factor 5 the volume of the waste disposed in the deep geological repository if compared to disposal of encapsulated spent UOX fuel (see discussion in *Cour des Comptes* [2012]).
- The interim storage period for the irradiated REPUOX and MOX fuel is assumed to be 50 years (before final disposal), and the cost of interim storage is assumed to be identical to UOX fuel for both spent REPUOX and MOX fuels.
- The spent MOX is cooled down in the interim storage facility, encapsulated and deposed of. The volume required for the disposal of the spent MOX is assumed[8] to be 2.5 times the volume needed for the disposal of the spent UOX fuel.
- The spent REPUOX is cooled down in the interim storage facility for 50 years, encapsulated and disposed (in the same way as the spent UOX in the direct disposal route, see Section 3.2.2).

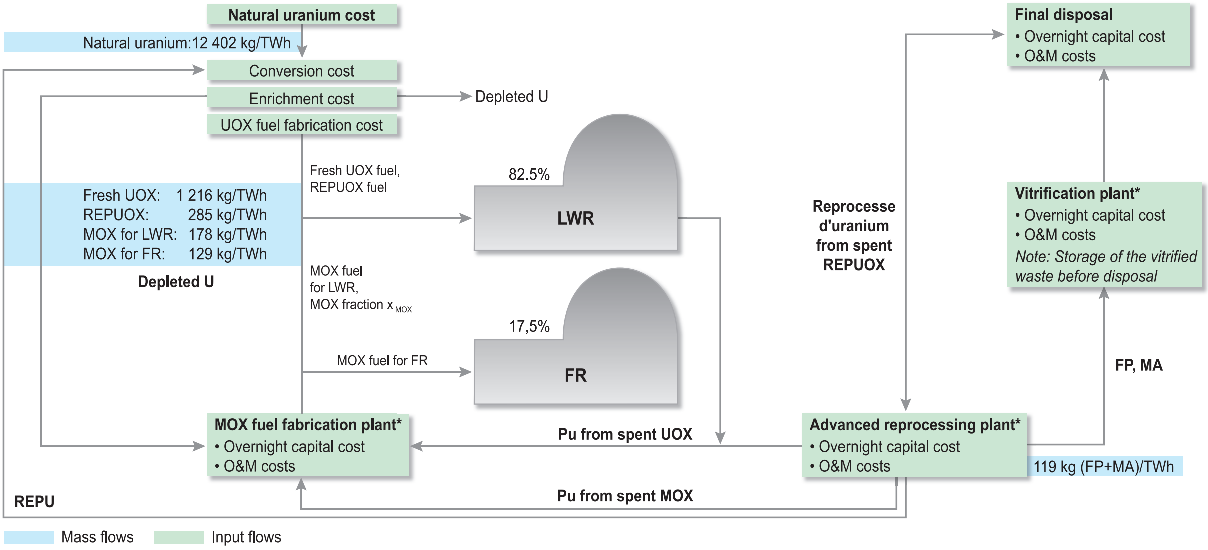
3.2.4. Multiple Pu recycling with LWRs and FRs route

The strategy *multiple plutonium recycling with LWRs and FRs* involves both LWRs and FRs, see Figure 3.10. Contrary to the strategy of partial recycling in LWRs, the used MOX and REPUOX fuels are not disposed but are reprocessed and recycled again as fuel in FRs. In

7. Needed because of the presence of neutron absorbing ^{236}U in the reprocessed uranium.
8. Based on decay heat ratios after about 50 years of storage, see ORNL (2011).

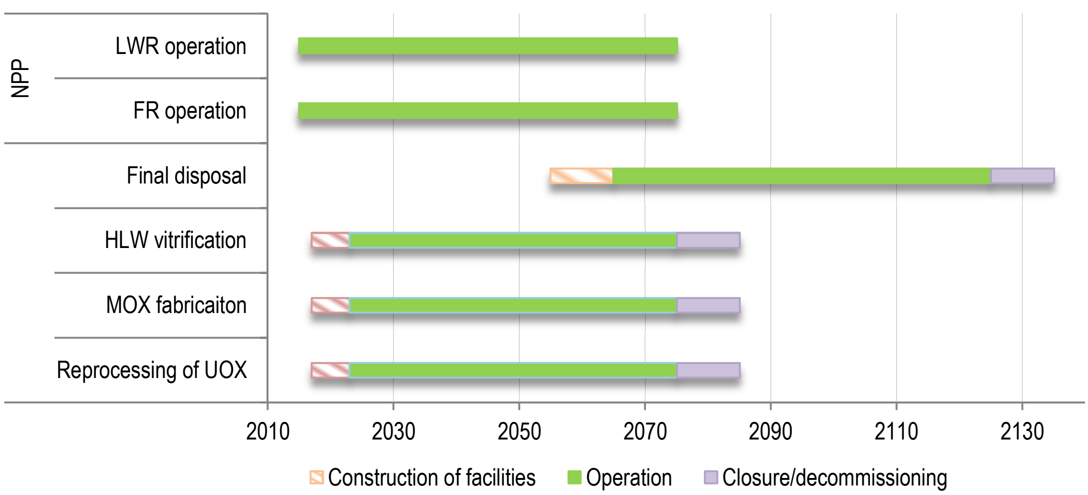
this idealised strategy, all the back-end facilities required for the management of the SNF produced by a fleet of NPPs (LWRs and FRs) operating between 2015[9] and 2075 (see Figure 3.11) are considered to be ready and operational exactly at the time and during the period when they are needed.

Figure 3.10: Multiple Pu recycling with LWRs and FRs route: MOX recycling once in LWRs and multiple recycling in FRs



* In the model an integrated reprocessing plant has been considered, including reprocessing, MOX fabrication and HLW vitrification facilities.

Figure 3.11: Construction schedules and operational periods of facilities involved in the realisation of multiple Pu recycling with LWRs and FRs route



9. In this idealised strategy it is assumed that LWRs and FRs are deployed simultaneously. This is a theoretical scenario; it is not envisaged that, in reality, FRs could be operational at industrial scale in 2015.

Fast reactors are expected to be more expensive than LWRs, thus a special cost premium for their construction and operation is introduced. This extra cost is attributed to the back-end component since, in this strategy, fast reactors are considered as a means for managing the SNF.

The following assumptions[10] were used in the reference case scenario:

- In this strategy, FRs are assumed to be sodium fast reactors (further details can be found in NEA (2006).
- FRs are considered as burners and not breeders (conversion ratios [CR] = 0.5).
- FRs have energy conversion efficiency of 40%.
- The value for the cost premium for sodium-cooled fast reactors[11] is assumed to be 20% on overnight capital costs and O&M costs compared to current investment cost in LWRs and O&M costs (these are assumed to be, respectively, USD 4 500/KWe and USD 10/MWh), i.e.:

$$\text{Cost premium}_{FR}=\frac{\sum_{t=T_{NPP,start}-T_{ref}}^{T_{NPP,end}-T_{ref}}\left(\frac{\left[\text{Investment}_t^{FR}-\text{Investment}_t^{LWR}\right]+\left[\text{O\&M}_t^{FR}-\text{O\&M}_t^{LWR}\right]}{(1+r)^t}\right)}{\sum_{t=T_{NPP,start}-T_{ref}}^{T_{NPP,end}-T_{ref}}\left(\frac{\text{Electricity}_t^{FR+LWR}}{(1+r)^t}\right)}$$

$$\text{Investment}_t^{FR}/\text{Investment}_t^{LWR} = 1.2, \qquad \text{O\&M}_t^{FR}/\text{O\&M}_t^{LWR} = 1.2$$

- The energy conversion efficiency of LWRs is assumed to be 34%.
- The enrichment of fresh UOX fuel is 4.95%.
- The additional enrichment[12] for the REPUOX fuel is 0.15%.
- 11% of power generated by LWRs is produced using MOX fuel bundles.
- The UOX and MOX_{LWR} fuel burn-up is 60 GWd/tHM.
- The MOX_{FR} fuel (fast reactors) burn-up is 140 GWd/tHM.
- The share of FRs (fuelled with MOX_{FR} fuel) in the fleet is 17.5%.
- Both irradiated UOX and MOX fuel are reprocessed and recycled after cooling down in spent fuel pools at NPP sites.
- LILW-LL streams generated during reprocessing are not considered in the calculations.
- The costs of FR fuel reprocessing and fuel fabrication from MOX_{FR} are assumed to be the same as the corresponding costs for thermal fuel.[13]

10. Based on NEA (2006 and 2002).
11. Given the relatively small share of FRs in the fleet (see Figure 3.10), no cost premium is applied for non-reactor facilities that are involved in fabrication and management of FR fuel.
12. Needed because of the presence of neutron absorbing ^{236}U in the reprocessed uranium.
13. Although it is not true in the case where a large amount of FR fuel is to be reprocessed (owing to increased costs associated with radiological protection, deterioration of the solvents, limitations due to criticality issues linked to higher Pu concentrations, etc.), if the share of FR fuel is less than 20%, it should still be possible to maintain the costs close to those corresponding to LWR fuel, as Areva's experience shows.

- The irradiated uranium is used to produce REPUOX fuel, which is recycled once in LWRs.
- The irradiated REPUOX is also recycled – the plutonium is reused and the uranium recovered from the spent REPUOX is disposed in the deep geological repository. Related costs for fuel reprocessing and fuel fabrication are assumed to be the same as the corresponding costs for thermal fuel.
- Separated fission products and minor actinides are vitrified and disposed after 50 years of cooling down (at the vitrification plant).
- As for the strategy of partial recycling in LWRs (see Section 3.2.3), it is assumed here that the separation and vitrification of fission products and minor actinides allow reducing the volume of the packaged waste to be disposed by a factor 5, if compared to disposal of encapsulated spent UOX fuel (see *Cour des Comptes*, 2012).
- At the end of all NPPs operational lifetime, the remaining irradiated UOX, REPUOX and MOX fuel from the fleet is disposed, and additional room in the final disposal is provided for this purpose.[14] As in the strategy of partial recycling in LWRs, the volume required for the storage of the spent MOX is assumed[15] to be 2.5 times the volume needed for the storage of the spent UOX.

3.2.5. Total overnight investment cost and O&M costs of back-end facilities

In addition to the definitions and assumptions presented above (and summarised in Figure 3.6 to Figure 3.11), overnight investment cost and O&M costs of different fuel cycle facilities constitute the basis for evaluating the fuel cycle costs of different strategies of SNF management.

Based on the data provided by member states and, where necessary, complemented with data from published sources, the following cost scenarios are considered for each facility:

- low cost scenario corresponding to the lower bound of cost estimated for a given facility, or for the most optimal realisation of a given strategy.
- reference cost scenario corresponding to the most likely value of cost according to the data available to date.
- high cost scenario corresponding to the upper bound of the costs for a given type of facility or service.

The difference between the low and high cost scenarios for each facility is derived from the spread of the data provided by the member countries, and it determines uncertainty bands in the final results. The *overnight capital investments* in different back-end facilities and the associated *O&M costs* depend on several factors including:

- the net capacity of the facility;
- the type of facility in the case where several technological options are available, e.g. wet or dry interim storage, final disposal in different geological environments, etc.;
- the design features of the facility;
- country-specific costs, e.g. of raw materials, manpower, taxes, etc.

14. This step is not shown in Figure 3.10 because it only takes place at the end.
15. Based on decay heat ratios after about 50 years of storage, see ORNL (2011).

In the subsections below, the data for different facilities are briefly discussed. The costs provided by member states were converted to the costs for the year 2010 using gross domestic product (GDP) deflators. Subsequently, they were converted from the national currency to 2010 USD using nominal exchange rates or purchase power parity (PPP) exchange rates (from OECD Statistics).

Based on the resulting data, overnight investment costs (OVC) and O&M costs for different facilities were parameterised as functions of capacity to yield curves corresponding to the low, reference and high cost scenarios. Except for the reprocessing facility, a linear law is adopted for the data parameterisation. The rationale behind this assumption is that most facilities have a significant fixed cost independent of the capacity, and a variable component proportional to the quantity of the SNF to be treated. This is, for example, the case of the dry interim storage facility, the SNF encapsulation plant, and the deep geological repository.

These parameterisations were used for the calculation of the levelised fuel cycle costs and their sensitivity to the variation of the OVC of individual facilities and other input parameters.

Interim storage

An interim storage facility is required for the implementation of the direct disposal strategy (storage of the spent UOX fuel) and the partial recycling in LWRs strategy (for the storage of the spent MOX and REPUOX).

Member countries' data for the costs of the interim storage facilities (both wet and dry storage), along with the resulting parameterisation curves, are provided in Figure 3.12 (overnight investment costs) and in Figure 3.13 (O&M costs). A linear law (with a fixed cost and a variable linear component) depending on the capacity of the facility is selected for the parameterisation of the overnight investment and O&M costs. This assumption primarily reflects the case of dry interim storage that is considered as the reference option in this section.

Figure 3.12: Interim storage facility: Overnight investment costs

(USD_{2010})

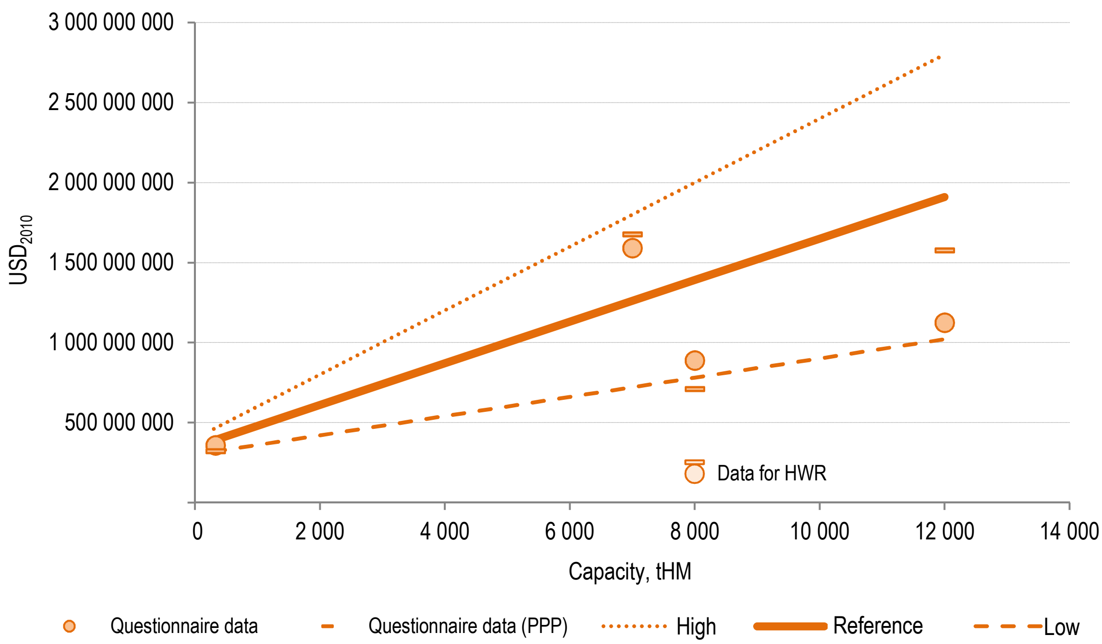
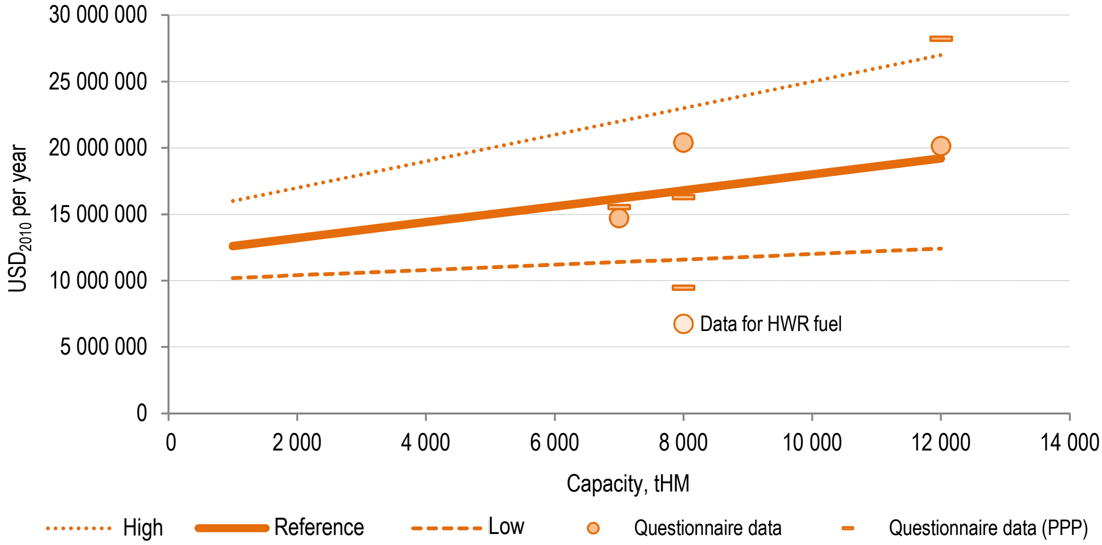


Figure 3.13: Interim storage facility: O&M costs

(USD_{2010} per year)



Integrated reprocessing, MOX fuel fabrication and FP/MA vitrification plant

Facilities for the reprocessing of spent nuclear fuel, MOX fuel fabrication and vitrification of the FP/MA HLW are required for the implementation of the *partial recycling in LWRs* and *multiple Pu recycling in LWRs and FRs* strategies.

Based on available economic data, an *integral reprocessing facility* is considered for the calculation of the fuel cycle costs, including:

- a reprocessing plant using aqueous technology;
- MOX fuel fabrication;
- FP/MA vitrification plant.

For systems smaller than 400 TWh/year, a centralised regional reprocessing plant is considered (located abroad), assumed to have a net capacity of 800 tHM/year and constructed with an interest rate of 3%. For larger systems a dedicated plant of the exact reprocessing capacity required is considered, and the discount rate used for the calculation is the same as for other facilities.

The data for the overnight investment costs of the integrated plant is taken from (*Cour des Comptes*, 2012) for historic costs (of EUR_{2010} 19.5 billion) of La Hague reprocessing plant and Melox MOX fuel fabrication plant in France, and (BCG, 2006) for projected costs of building a new generation integrated plant (see Figure 3.14). In addition, and for comparison purposes, one can quote the capital cost of THORP of 1 200 tHM/year nominal capacity in the United Kingdom that was estimated[16] at GBP_{1994} 2 500 million (i.e. about USD_{2010} 5.32 billion), and the recently announced capital cost of the Mixed Oxide Fuel Fabrication Facility[17] that was estimated by the US Government Accountability Office at USD 7.7 billion.[18]

16. This estimate also includes the cost of associated effluent/waste plants.
17. The Mixed Oxide Fuel Fabrication Facility that will transform about 3.5 tonnes of weapons-grade plutonium per year into MOX fuel assemblies is being constructed in the United States.
18. See www.gao.gov/products/GAO-13-484T for details.

For the parameterisation of the overnight investment costs, a scaling law approach is used (see Peters *et al.*, 2002 and Shropshire *et al.*, 2009) with a scaling factor of 0.6. Thus, the OVC of two integrated plants of different capacities are related by the following law:

$$\text{OVC(capacity1)} = \text{OVC(capacity2)} \left(\frac{\text{capacity1}}{\text{capacity2}}\right)^{n}, \ n=0.6$$

The data point corresponding to the historical cost of La Hague (*Cour des Comptes*, 2012) is parameterised within the high cost scenario since the estimate by the (*Cour des Comptes*) (blue triangle in Figure 3.14) gives the historical cost for this first-of-a-kind plant at La Hague. Moreover, La Hague plant consists of two largely independent facilities UP2-800 and UP3 of net capacity 800 tHM/year each.

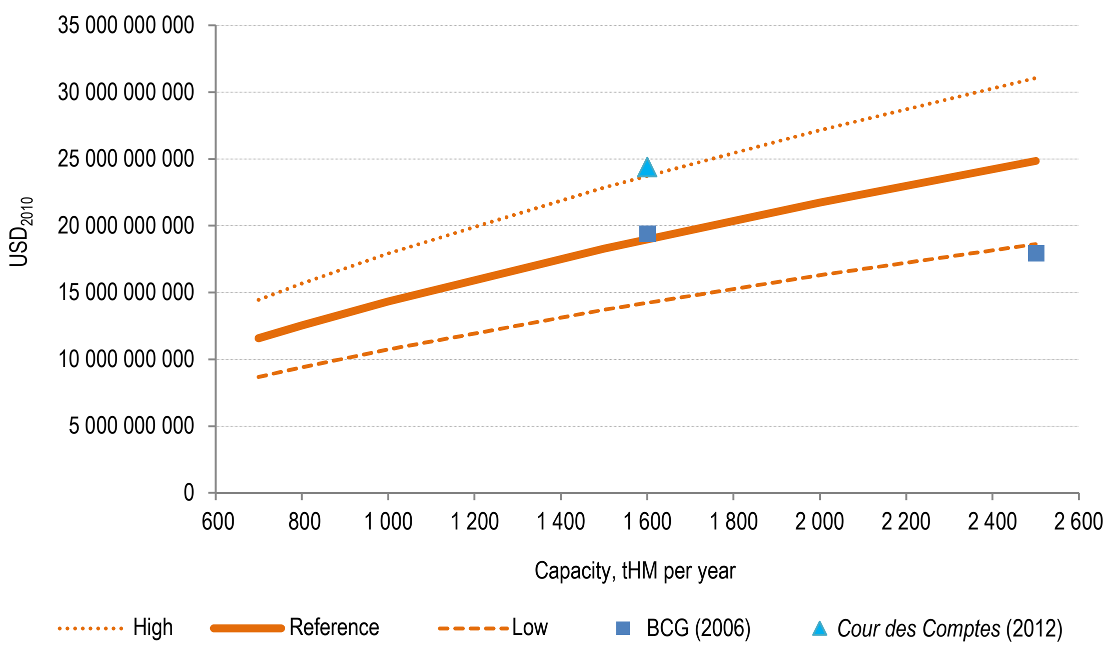
If rebuilt today, the plant of effective reprocessing capacity of 1 600 tHM/year and integrated with a MOX fuel fabrication plant and HLW vitrification facility would have lower capital costs (see discussion in BCG [2006]). This case is considered as the reference case scenario in the present study.[19]

The low cost case scenario is based on the estimate for a large reprocessing plant (of 2 500 tHM/year) for the US market provided in BCG (2006). In this estimate, significant improvements and economies of scale have been envisaged.

O&M costs are presented in Figure 3.15. Based on the data available, a scaling factor of 0.4 is used for the parameterisation of O&M costs.

Figure 3.14: Integrated reprocessing plant: Overnight investment costs

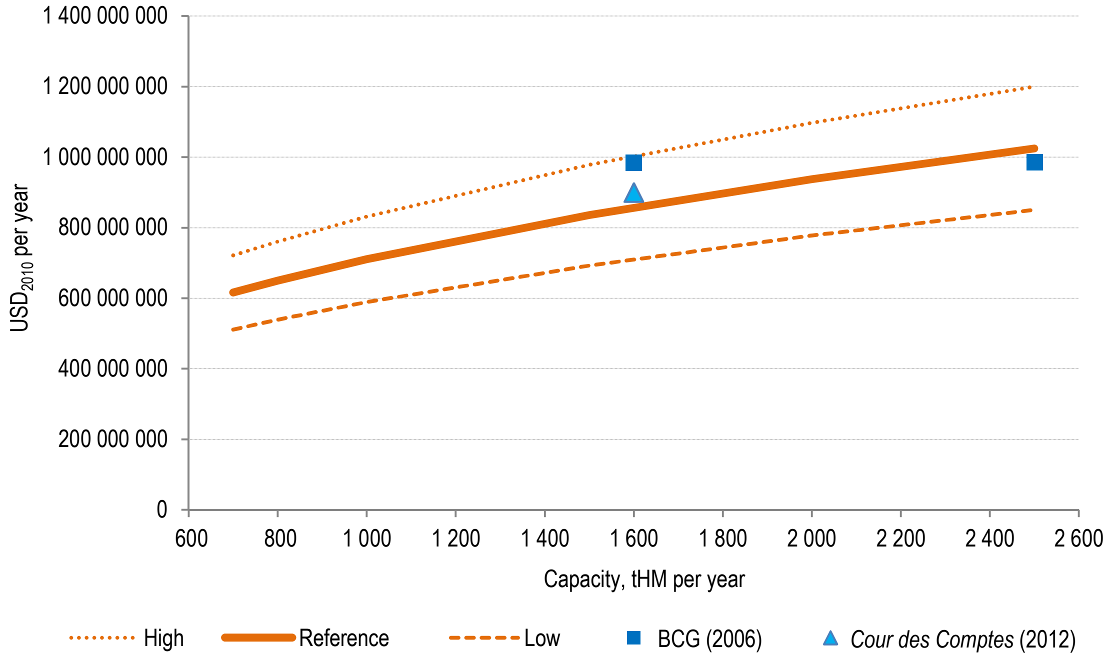
(USD_{2010})



19. OVC_{high} (1 600 tHM/year), corresponding to the historical data for La Hague, is roughly equal to $2 \times OVC_{reference}$ (800 tHM/year), which shows some internal consistency between the reference and high parameterisation laws.

Figure 3.15: Integrated reprocessing plant: O&M costs

(USD2010 per year)



The specific costs (per kgHM) of reprocessing obtained through this parameterisation exercise is illustrated in Table 3.3 for different plant capacities and for different discount rates.

Table 3.3: Specific cost of reprocessing within different cost scenarios and discount rates

Reprocessing plant capacity, tHM/year	Cost scenario	Total specific cost of reprocessing, USD/kgHM		
		Discount rate		
		0%	3%	7%*
800	low	933	1 170	1 687
	reference	1 159	1 474	2 163
	high	1 384	1 779	2 640
1 600	low	467	585	843
	reference	579	737	1 082
	high	692	889	1 320

* Provided to illustrate differences between publicly and privately funded facilities.

SNF encapsulation plant

The overnight investment costs and O&M costs for the SNF encapsulation plant are given in Figure 3.16 and Figure 3.17 respectively. A linear law is adopted for parameterisations of these sets of data, with a fixed cost component and a variable cost component proportional to the capacity. An uncertainty range of ±25% around the reference case is adopted to define low and high cost scenarios. It is recognised that the data here are very limited.

Figure 3.16: SNF encapsulation plant: Overnight investment costs

(USD_{2010})

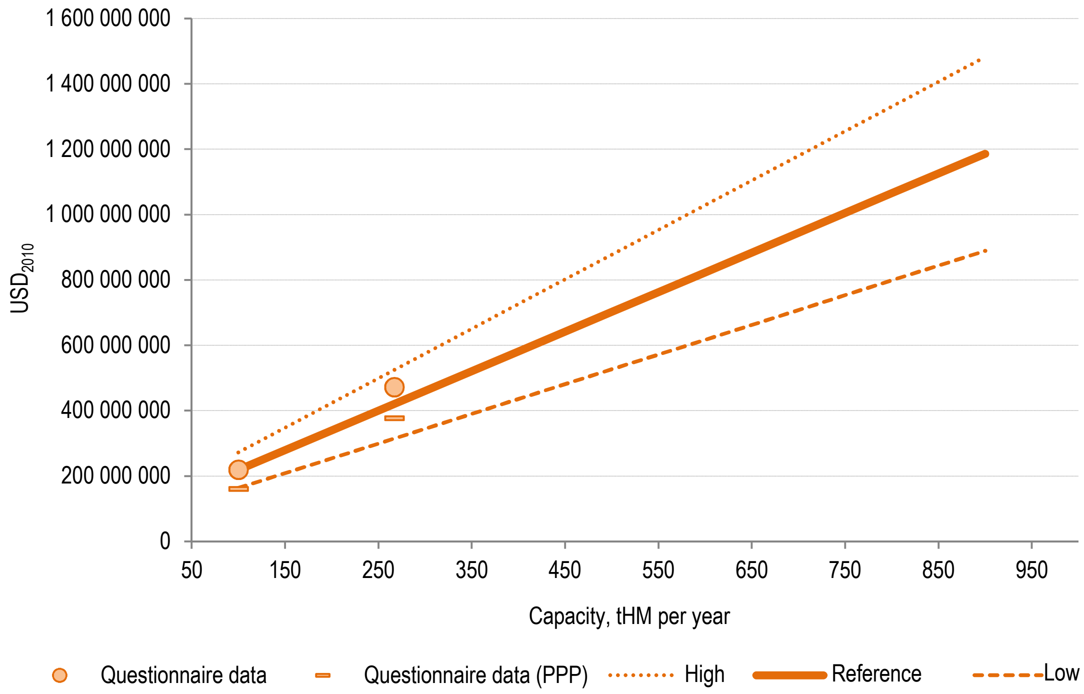
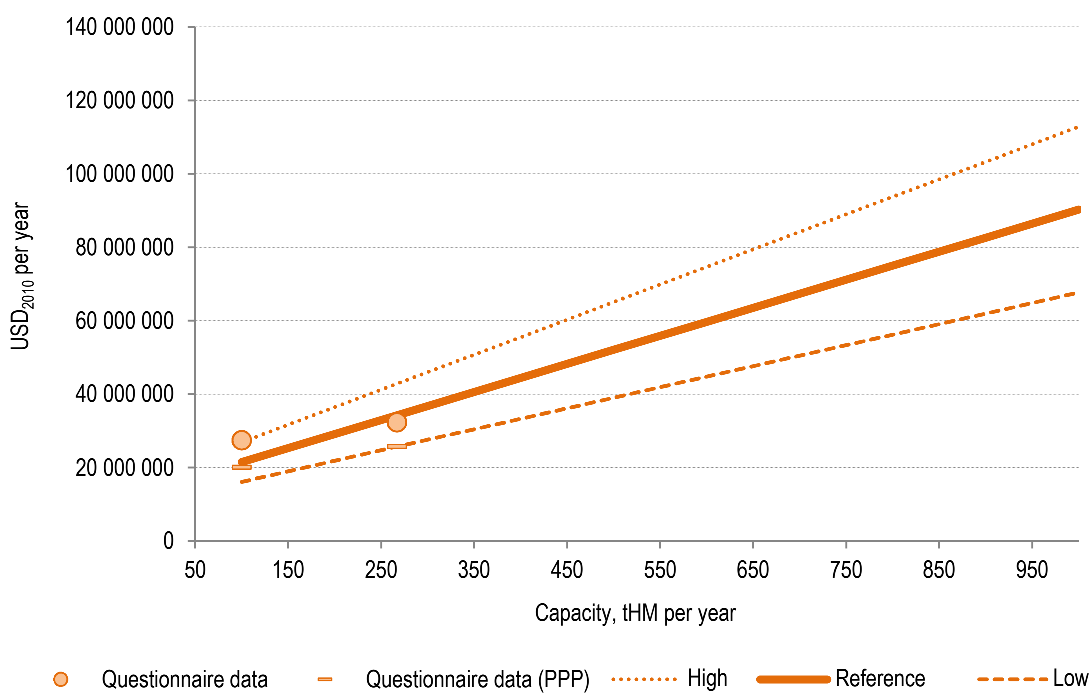


Figure 3.17: SNF encapsulation plant: O&M costs

(USD_{2010} per year)



Geological repository

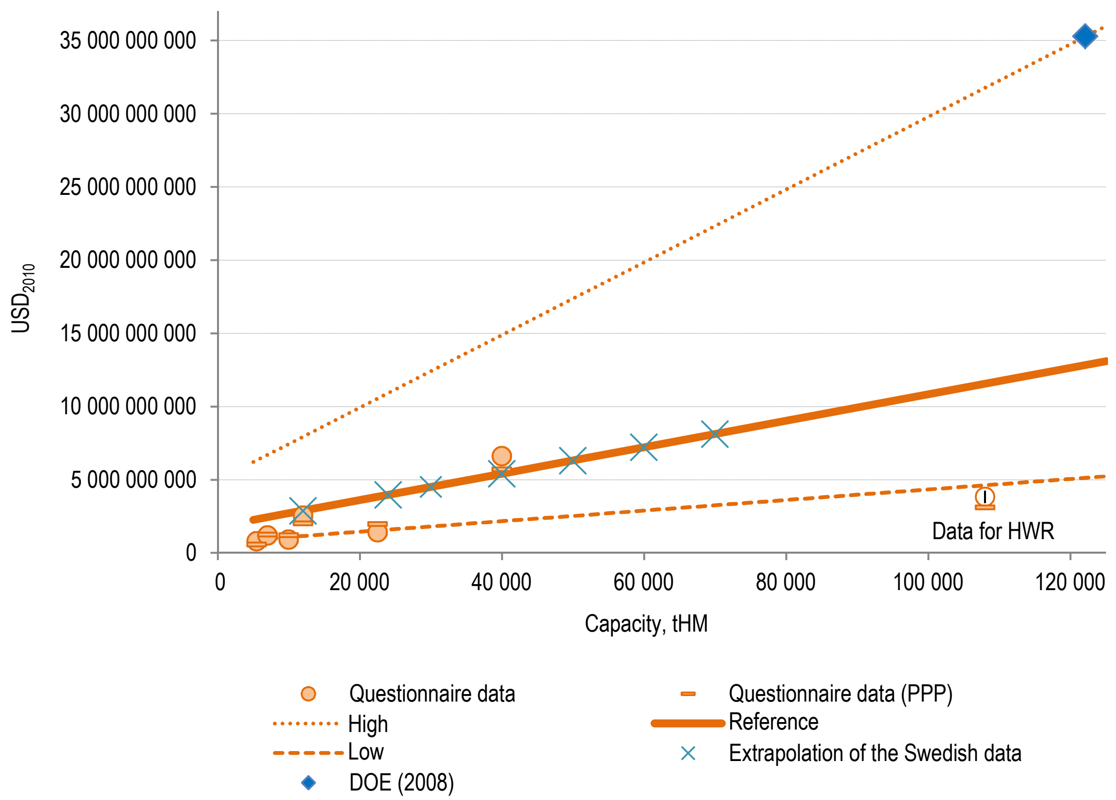
The data points and assumptions on overnight investment costs for the DGR are shown in Figure 3.18, O&M costs are reported in Figure 3.19[20] and closure costs in Figure 3.20. Data on these graphs correspond to the current estimates of costs of geological repositories provided by member countries, and refer to different situations, notably different locations, geological environments (e.g. disposal in granite, clay or salt) and regulatory frameworks. No civilian DGR is in operation to date; DGR cost estimates can only be ultimately verified as facilities are constructed.

A linear law is selected for the parameterisation of the estimates of the overnight investment and O&M costs. The fixed component of the overnight investment cost corresponds to the investment in surface facilities, shaft construction and other costs independent of the capacity of the repository. The variable component is proportional to the volume of material excavated underground. The closure costs (given in Figure 3.20) were assumed to be independent of the repository capacity.

The examples in Table 3.4 illustrate the specific overnight investment costs (in USD_{2010}/kgHM) for three different capacities of repositories: 20 000 tHM, 40 000 tHM and 120 000 tHM obtained through the parameterisations described above.

Figure 3.18: Geological repository: Overnight investment cost

(USD_{2010})



20. The curves in Figure 3.19 show O&M costs for different strategies assuming an operational period of the DGR of 60 years.

Figure 3.19: Geological repository: Annual O&M costs (normalised for 60 years of operation)

(USD2010 per year)

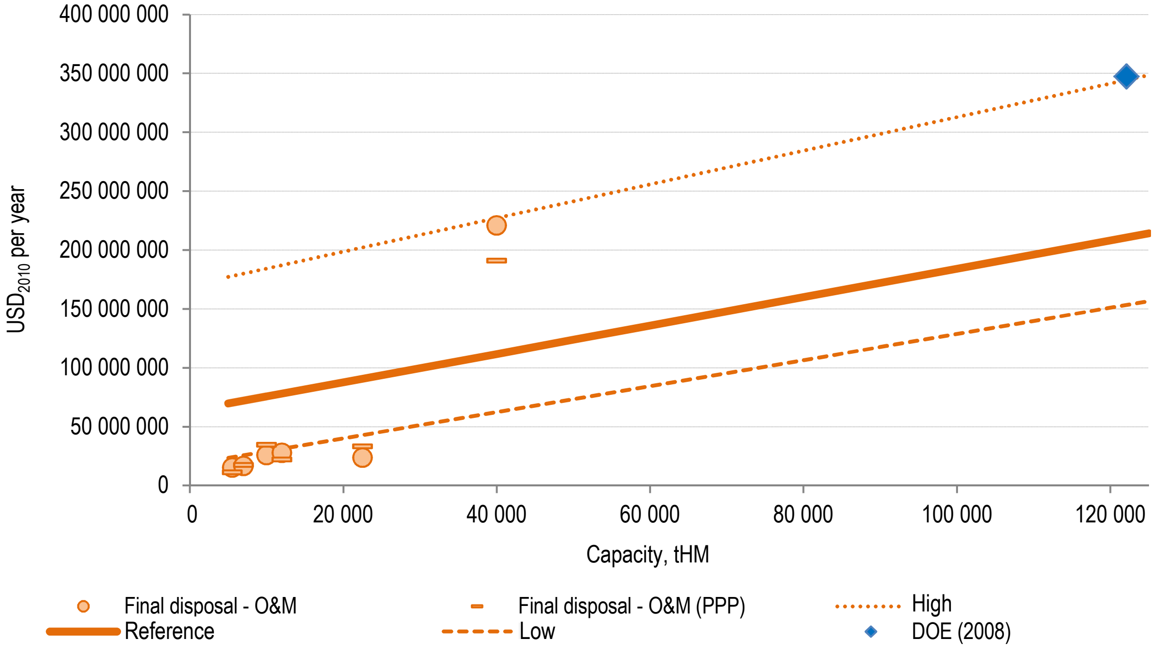
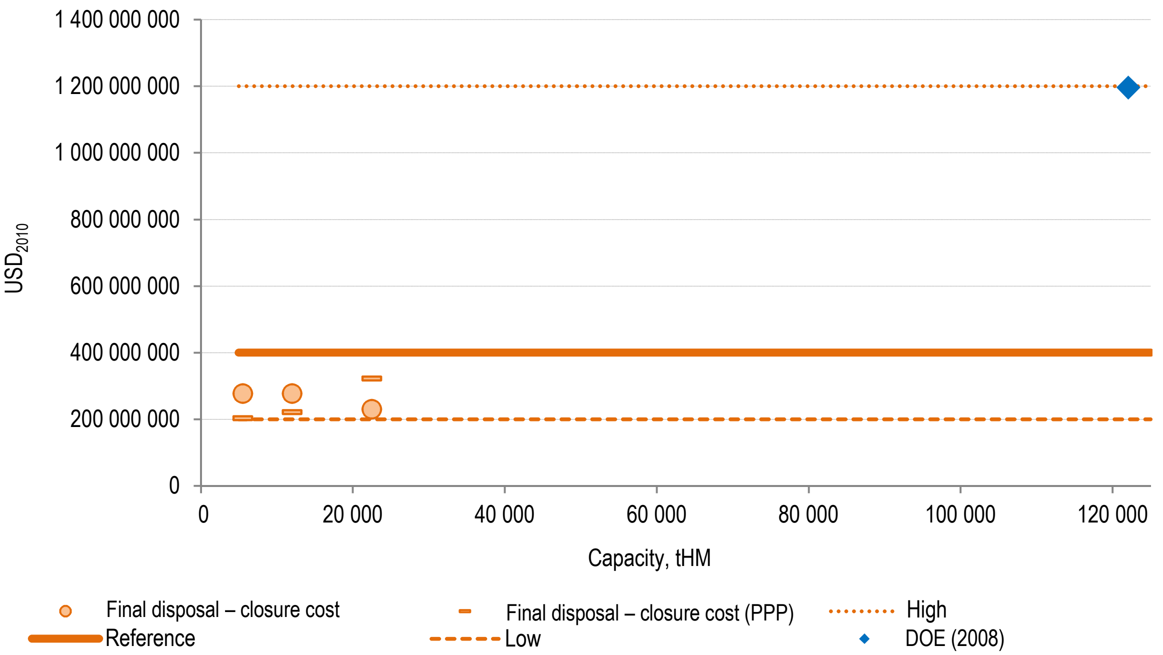


Figure 3.20: Geological repository: Closure costs

(USD2010)



Note: The data from DOE (2008) in Figures 3.18-3.20 correspond to the Yucca Mountain project. Preliminary DGR cost estimates performed by a consortium of the DOE's national laboratories for various types of geologic media (see DOE, 2013) suggest that costs for the new repository could vary from the base case corresponding to the Yucca Mountain project (reported in DOE, 2008) and may increase by ~80% if the repository were sited in the most expensive geological medium or decrease by ~50% if the repository were sited in the least expensive one.

Table 3.4: Overnight repository costs for different capacities (in the direct disposal strategy)

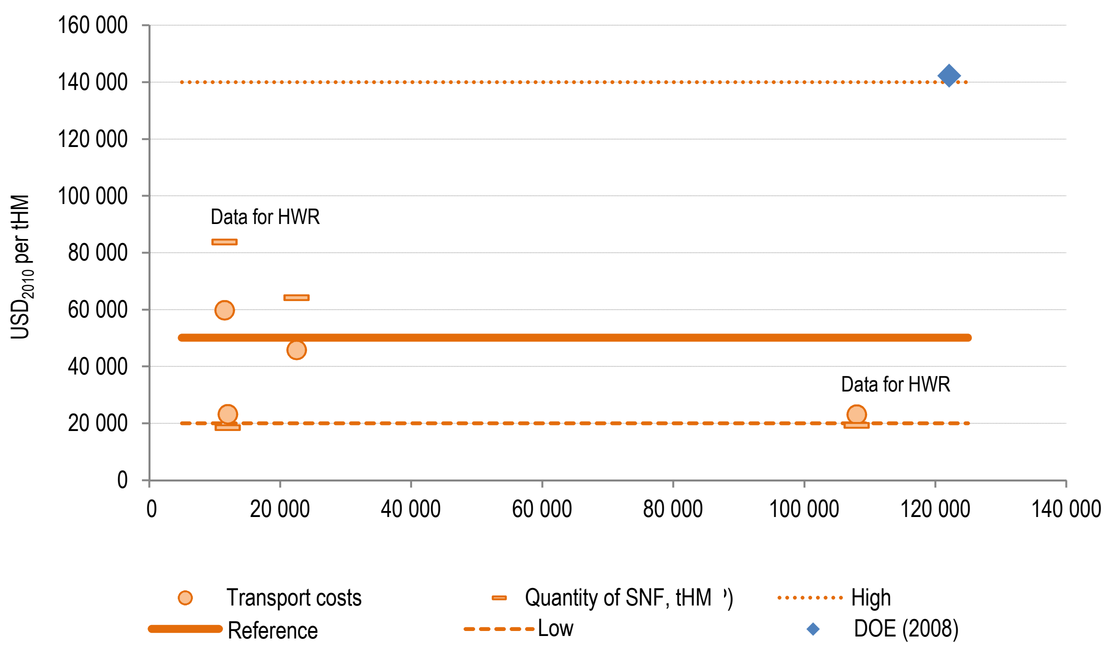
Repository capacity, tHM	Cost scenario	Capital investment, USD_{2010} billion	Annual operation costs, USD_{2010} million	Duration of operation, years	Closure costs, USD_{2010} million	Total specific cost at 0% discount rate, USD/kgHM
20 000	low	1.44	40	60	200	203
	reference	3.61	88	60	400	464
	high	9.93	199	60	1 200	1 152
40 000	low	2.17	62	60	200	153
	reference	5.42	112	60	400	313
	high	14.89	227	60	1 200	743
120 000	low	5.05	151	60	200	119
	reference	12.64	208	60	400	213
	high	34.75	341	60	1 200	470

Transport costs

The transport costs associated with the transport of the SNF to the interim storage, reprocessing plant, encapsulation plant or final disposal, are expressed as USD/tHM. Specific values derived from the data supplied by member countries are given in Figure 3.21.

Figure 3.21: Specific transport costs

(USD per tHM)



3.2.6. Modelling results

The results of the calculation of $LCOE_{Fuel\ cycle}$ for the three strategies using the definitions and assumptions reported in previous sections (3.2.1 to 3.2.5), are provided in Figure 3.22 for 0% and 3%, since low discount rates are preferred for long-term public benefits projects.[21]

The detailed breakdowns of specific, per MWh, levelised fuel cycle costs are shown in Figure 3.23 to Figure 3.26 for four generic fleet sizes with electricity capacities[22, 23] of: 25 TWh/year, 75 TWh/year, 400 TWh/year and 800 TWh/year. The total net present costs of implementation of different back-end strategies is given in Table 3.5 for 0% and 3% discount rates.

The following general observations can be drawn from these results:

- In all strategies considered, the fuel cycle cost component associated with the management of SNF is a relatively small fraction of the total levelised cost of electricity generation.

  As an illustration, the historical cost of electricity generation in France was estimated by the *Cour des Comptes* at about USD 60/MWh. According to the results of this analysis, the total fuel cycle cost then would represent less than 13%, and the back-end cost would be about 6.5% of this historical cost. However, even these small fractions could translate into large absolute costs depending on the size of the nuclear programme and the period of electricity generation.

- The total fuel cycle costs calculated for the reference case are lower for the open fuel cycle option. Given the uncertainties related to cost estimates and their sensitivity to discount rate, however, the difference between the total fuel cycle costs of the three options considered in the reference cost scenario are within the uncertainties. Additional costs from reprocessing are being offset by the savings on fuel costs at the front end.

- The specific costs decrease with the size of the system. Thus, there may be economic benefits in sharing different fuel cycle facilities between countries/utilities:

  – For small systems, fixed costs are more dominant, so costs rise over-proportionally as the system size decreases (see Figure 3.22).

  – For small systems, uncertainties become also larger. This effect is partly attributable to the fact that the amount of electricity generated is smaller (which has an impact when calculating levelised costs), but, importantly, it is also related to the selection of the upper bound curves in the parameterisation.

21. For illustrative purposes, the results for a 7% real discount rate are provided in Appendix 5.

22. Assuming an energy availability factor of 85%, this roughly corresponds to the fleets with 3.5, 10, 55 and 107 GWe installed nuclear power, respectively.

23. For very small systems, higher front-end costs would probably be more appropriate. However, for consistency, the same front-end assumptions were used for all system sizes.

Table 3.5: Net present cost* of implementation of different back-end strategies**, in USD billions

(0% discount rate)

	25 TWh/year			75 TWh/year			400 TWh/year			800 TWh/year		
	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC
Net present cost of implementation of different back-end strategies												
Low	5.2	7.2	7.1	7.4	13.6	16.0	21.3	54.8	73.6	38.5	70.7	101.6
Reference	10.7	13.0	12.6	14.8	22.0	23.7	41.4	80.3	96.4	74.1	107.5	131.0
High	23.8	26.2	25.0	32.1	39.7	39.8	85.8	127.0	136.2	151.9	180.2	187.8
Savings from reduced fuel requirements compared to direct disposal route												
		-1.8	-3.0		-5.3	-8.9		-28.4	-47.4		-56.7	-94.8
Net present cost taking into account the savings from reduced fuel requirements compared to the direct disposal route												
Low	5.2	5.4	4.1	7.4	8.3	7.1	21.3	26.4	26.2	38.5	14	6.8
Reference	10.7	11.2	9.6	14.8	16.7	14.8	41.4	51.9	49	74.1	50.8	36.2
High	23.8	24.4	22	32.1	34.4	30.9	85.8	98.6	88.8	151.9	123.5	93

(3% discount rate)

	25 TWh/year			75 TWh/year			400 TWh/year			800 TWh/year		
	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC	OFC	Partial recycling	AFC
Net present cost of implementation of different back-end strategies												
Low	1.5	3.7	4.5	2.2	9.1	12.5	6.7	44.7	64.8	12.2	66.9	102.4
Reference	2.7	5.3	6.2	4.2	12.5	16.0	13.6	59.5	80.3	25.2	90.2	126.0
High	5.4	8.4	9.2	8.2	17.9	21.3	26.4	79.7	100.1	48.8	123.4	157.1
Savings from reduced fuel requirements compared to direct disposal route												
		-1.8	-3.0			-8.9		-28.4	-47.4		-56.7	-94.8
Net present cost taking into account the savings from reduced fuel requirements compared to the direct disposal route												
Low	1.5	1.9	1.5	2.2	3.8	3.6	6.7	16.3	17.4	12.2	10.2	7.6
Reference	2.7	3.5	3.2	4.2	7.2	7.1	13.6	31.1	32.9	25.2	33.5	31.2
High	5.4	6.6	6.2	8.2	12.6	12.4	26.4	51.3	52.7	48.8	66.7	62.3

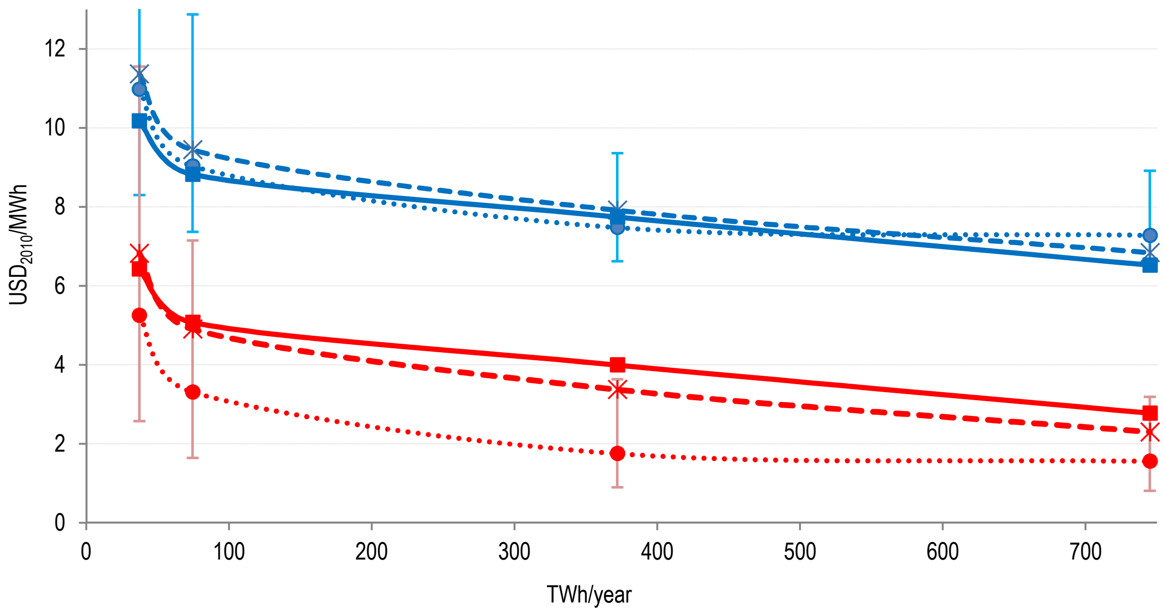
* These net present values are in absolute USD. The LCOE is obtained as the ratio of these values to the total electricity generated.

** In this table the three strategies defined in section 3.2 are referred to as:

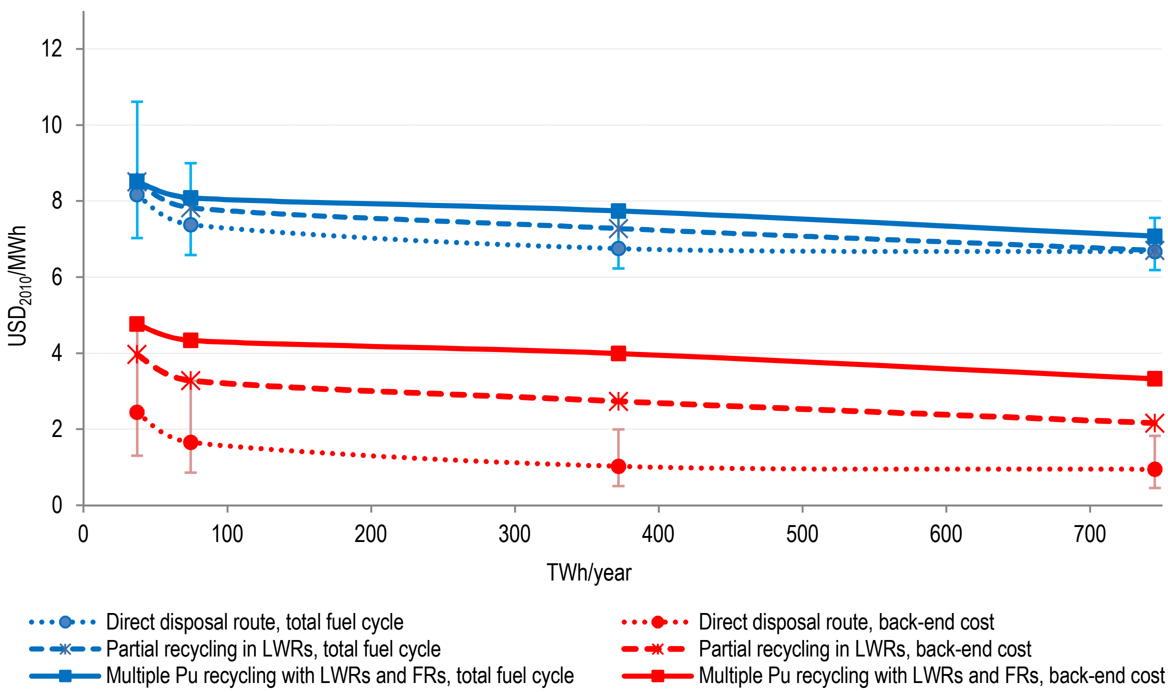
1. OFC (once-through fuel cycle) for the direct disposal of SNF.
2. Partial recycling (in LWRs).
3. AFC (advanced fuel cycle) for the multiple Pu recycling with LWRs and FRs.

Figure 3.22: $LCOE_{Fuel\ cycle}$ and $LCOE_{Back\text{-}end}$ for different reactor fleets and back-end strategies*

(0% discount rate)



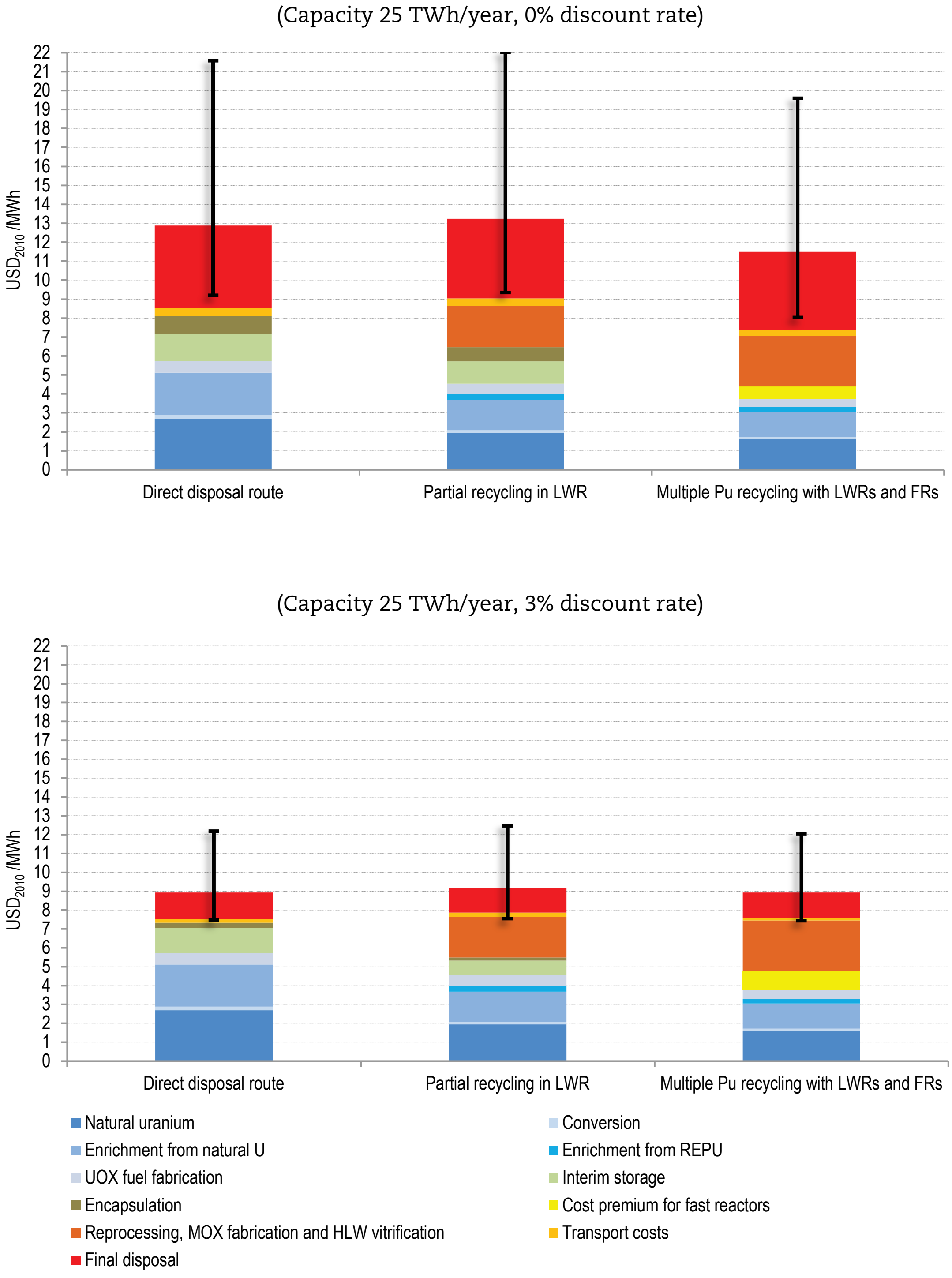
(3% discount rate)



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

* Uncertainty bands are only plotted for the direct disposal case. Similar bands apply to the other options, as shown in Figures 3.23 to 3.26.

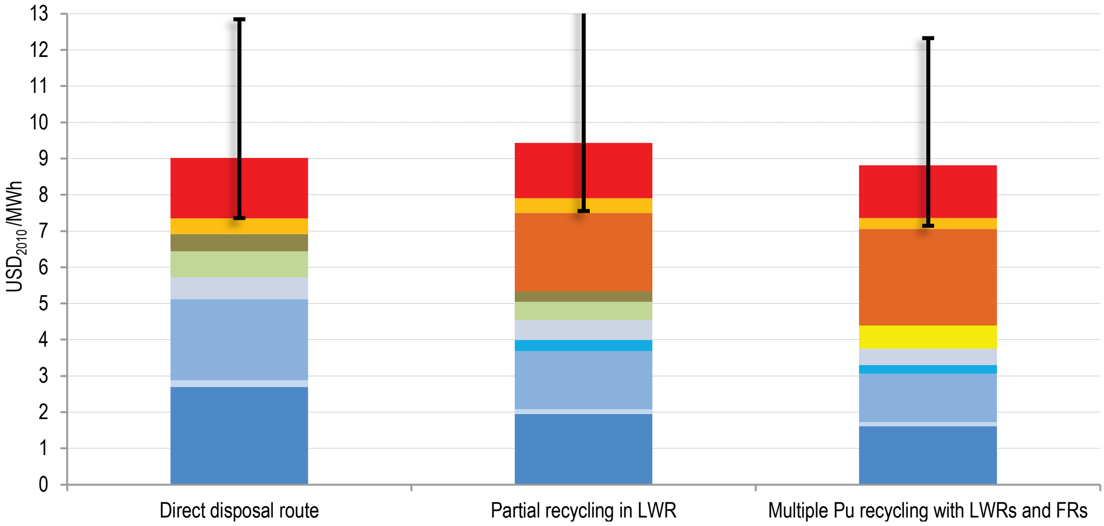
Figure 3.23: Fuel cycle cost breakdown for different strategies, for a fleet generating 25 TWh/year, in the reference cost scenario, at 0% and 3% discount rates



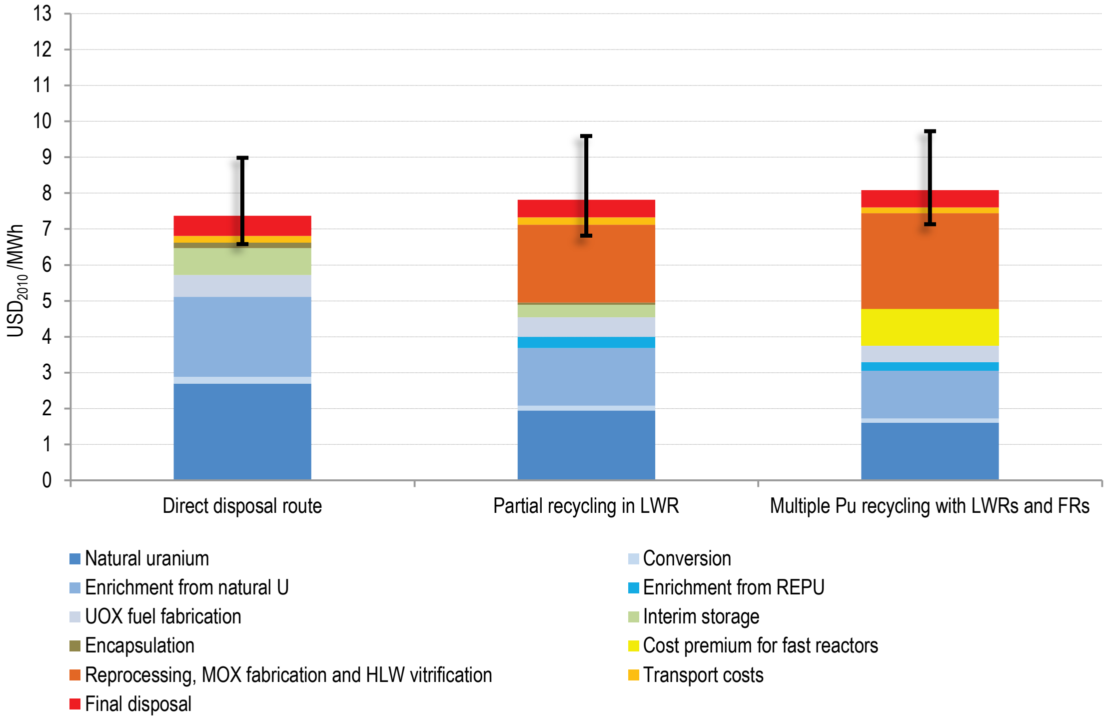
Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

Figure 3.24: Fuel cycle cost breakdown for different strategies, for a fleet generating 75 TWh/year, in the reference cost scenario, at 0% and 3% discount rates

(Capacity: 75 TWh/year, discount rate 0%)

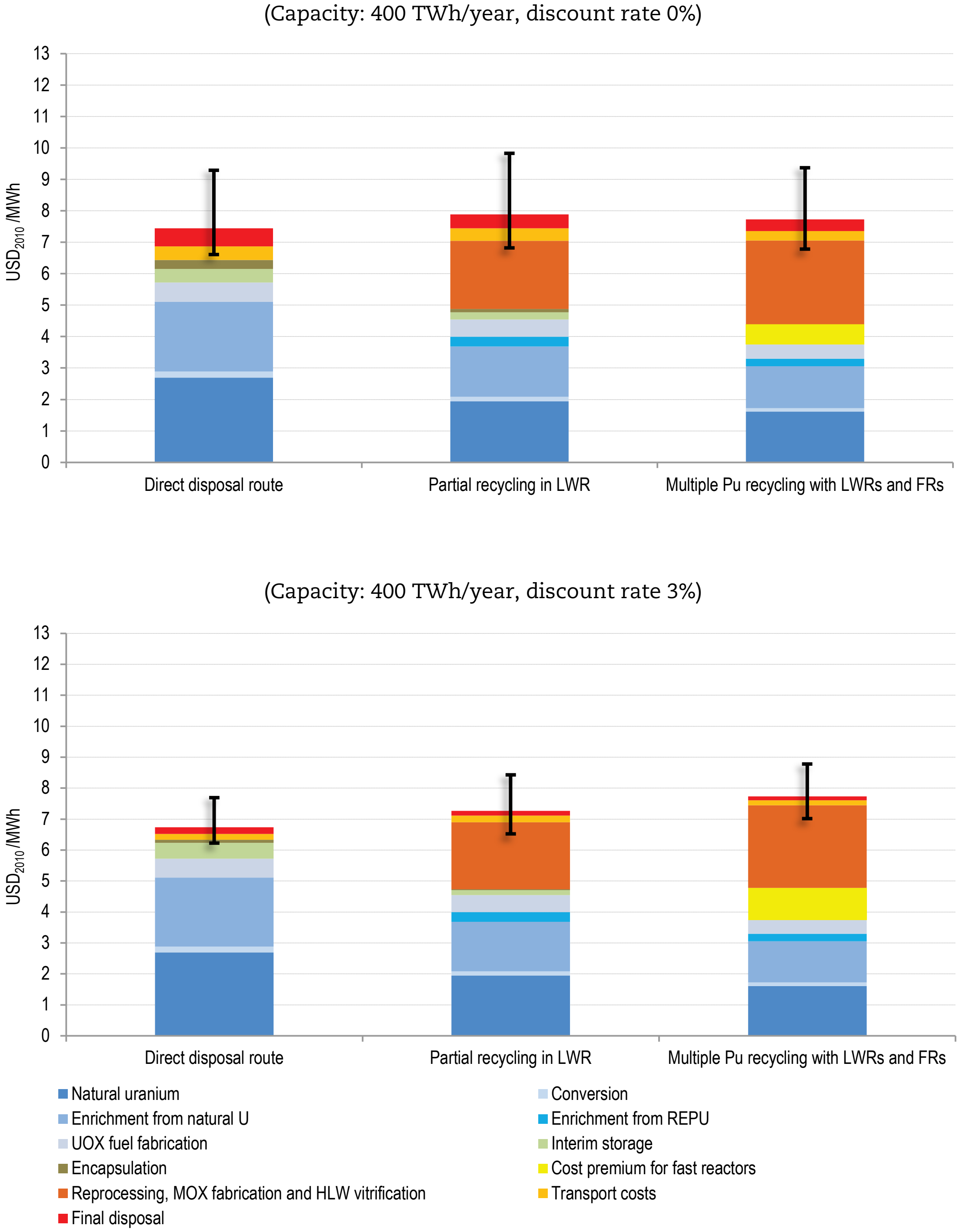


(Capacity: 75 TWh/year, discount rate 3%)



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

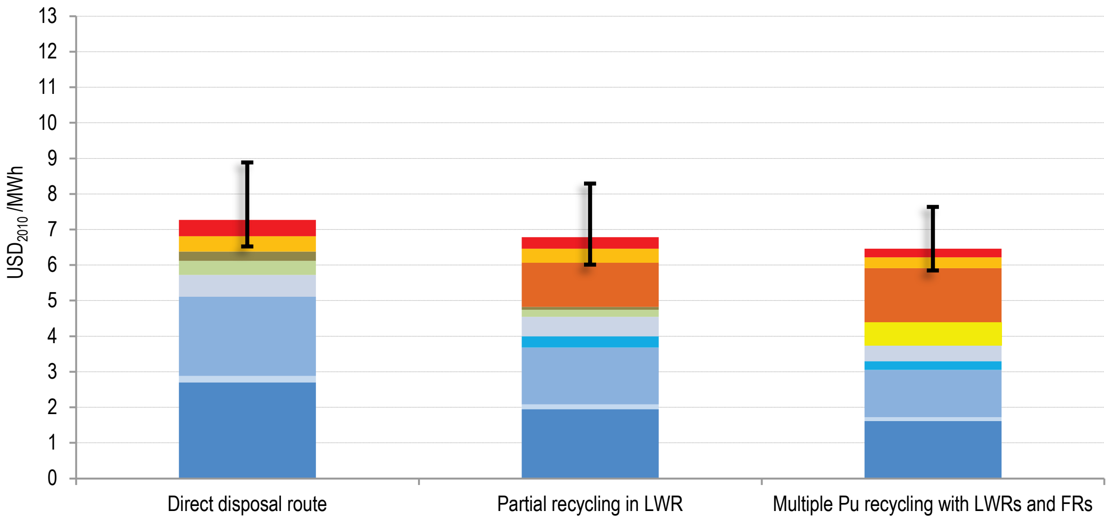
Figure 3.25: Fuel cycle cost breakdown for different strategies, for a fleet generating 400 TWh/year, in the reference cost scenario, at 0% and 3% discount rates



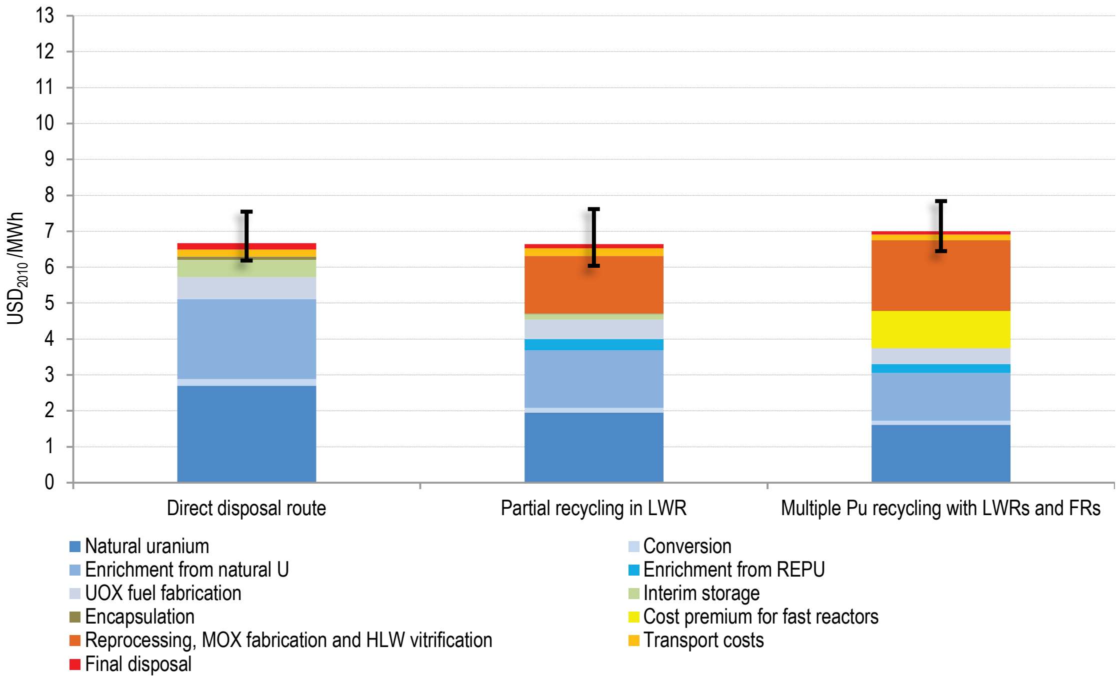
Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

Figure 3.26: Fuel cycle cost breakdown for different strategies, for a fleet generating 800 TWh/year, in the reference cost scenario, at 0% and 3% discount rates

(Capacity: 800 TWh/year, discount rate 0%)



(Capacity: 800 TWh/year, discount rate 3%)



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

3.2.7. Sensitivity analysis

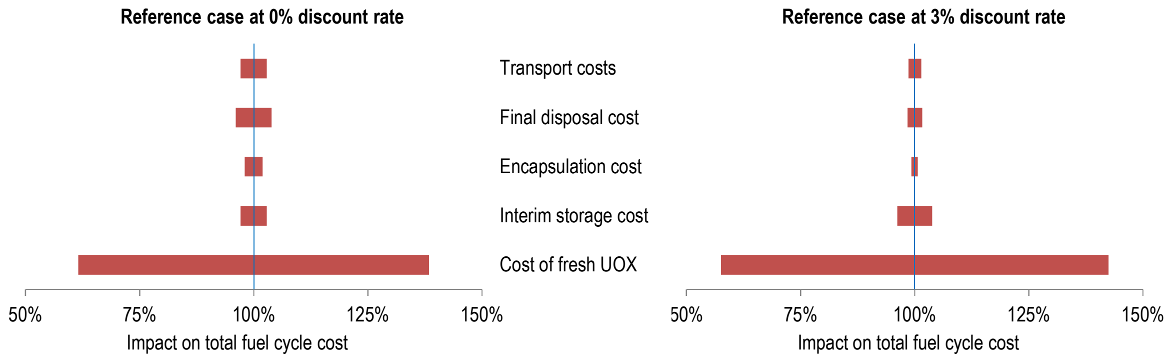
This section presents a detailed sensitivity analysis of the levelised fuel cycle costs to different parameters, in particular to discount rate, cost of fresh UOX fuel, cost premium for fast reactors and the implementation schedule.

Sensitivity to cost components

To illustrate the sensitivity of the $LCOE_{Total\ fuel\ cycle}$ to the cost variations of the components, a ±50% change on cost components (one by one) has been applied for two values of discount rate (0% and 3%) for a 400 TWh/year system. The results are presented in Figure 3.27.

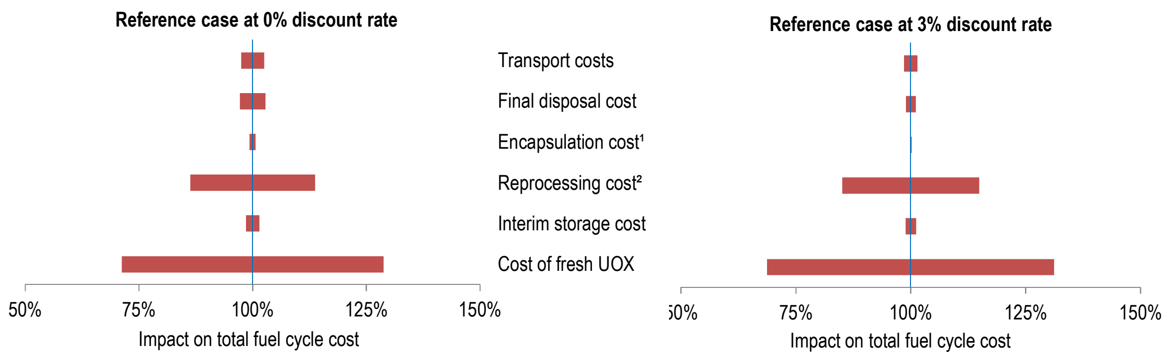
Figure 3.27: Impact on the $LCOE_{Total\ fuel\ cycle}$ of ±50% cost change, for a 400 TWh/year system

Direct disposal route



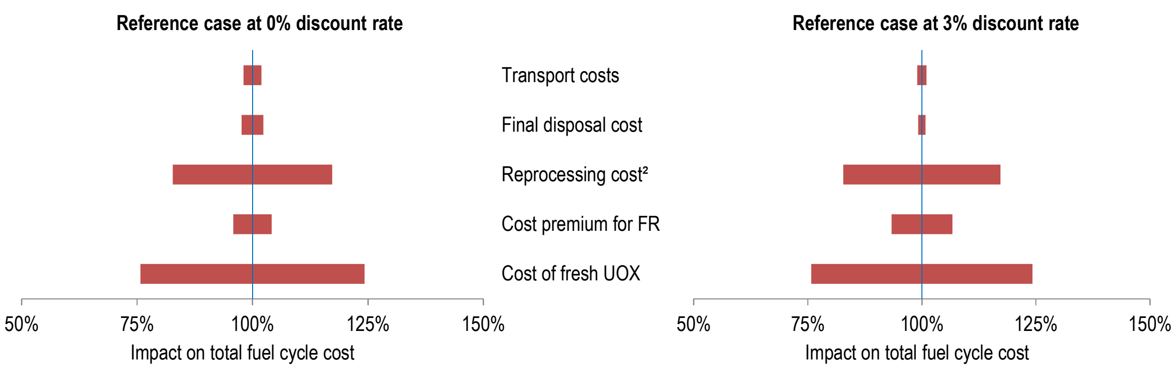
Partial recycling in LWR

(Twice-trough (REPUOX and MOX) and disposal of the spent MOX and spent REPUOX)



Multiple Pu recycling with LWRs and FRs

(MOX and REPUOX recycling once in LWRs and multiple plutonium recycling in FRs)



1. Encapsulation of spent MOX and REPUOX.
2. Reprocessing of SNF, MOX fabrication and HLW vitrification.

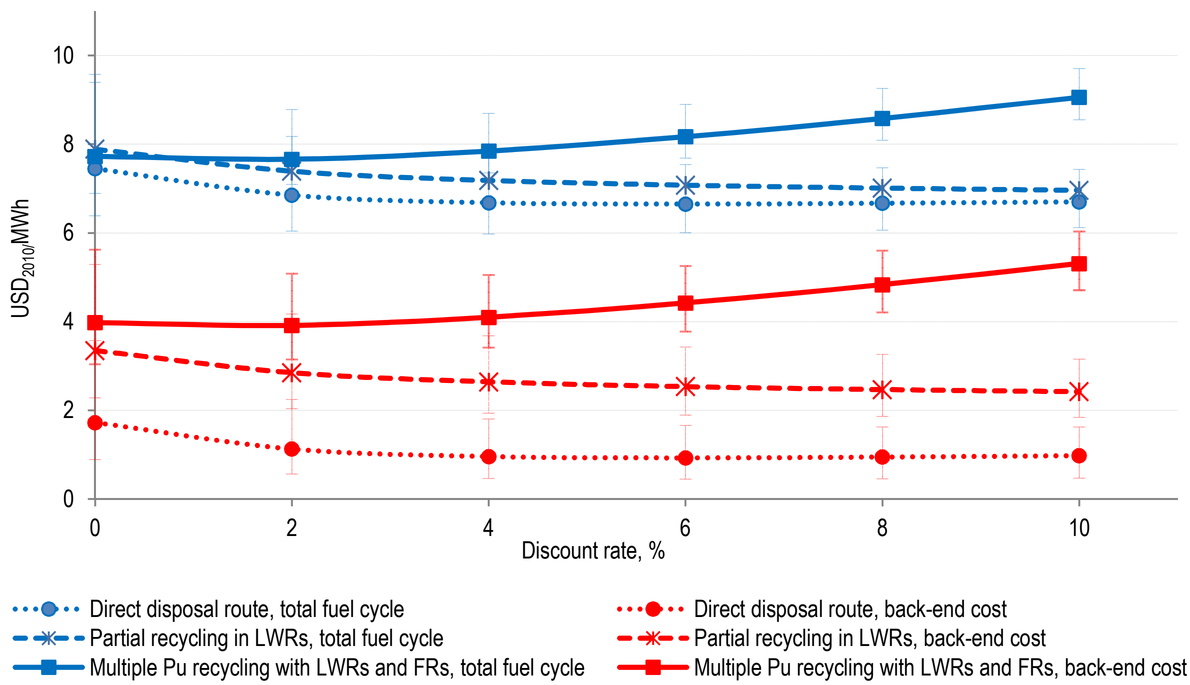
In all three strategies, the total fuel cycle cost is most sensitive to the cost of fresh UOX. The next largest sensitivities in the *direct disposal of spent nuclear fuel* strategy are to the costs of the interim storage and of the DGR. Following the cost of the fresh UOX, the *partial recycling in LWRs* strategy is most sensitive to the cost of reprocessing, as it is the case also for *the multiple Pu recycling with LWRs and FRs* strategy; for this latter case, the cost premium for fast reactors has also an important impact.

In particular one could note that, in spite of the relatively large uncertainties in the DGR cost data (see Figures 3.18-3.20), the impact on the fuel cycle cost is small, while the impact of uncertainties of the cost of fresh UOX fuel and reprocessing have a stronger impact.

Sensitivity to discount rate

The discount rate is one of the key economic parameters for fuel cycle cost calculations. Since the strategies are implemented over large periods of time, any non-zero (and positive) discount rate significantly decreases the contribution to the levelised cost of the expenses appearing after the end of NPP operation. The sensitivity analysis is performed for a large interval of real discount rates 0-10%, although it is recognised that low discount rates should be preferred for long-term public benefits projects. In Figure 3.28, the total fuel cycle costs for the three SNF management strategies considered in this chapter are presented as a function of the real discount rate, for a fleet of NPPs generating 400 TWh/year.

Figure 3.28: Fuel cycle costs for different back-end strategies as function of discount rate, for a fleet generating 400 TWh/year

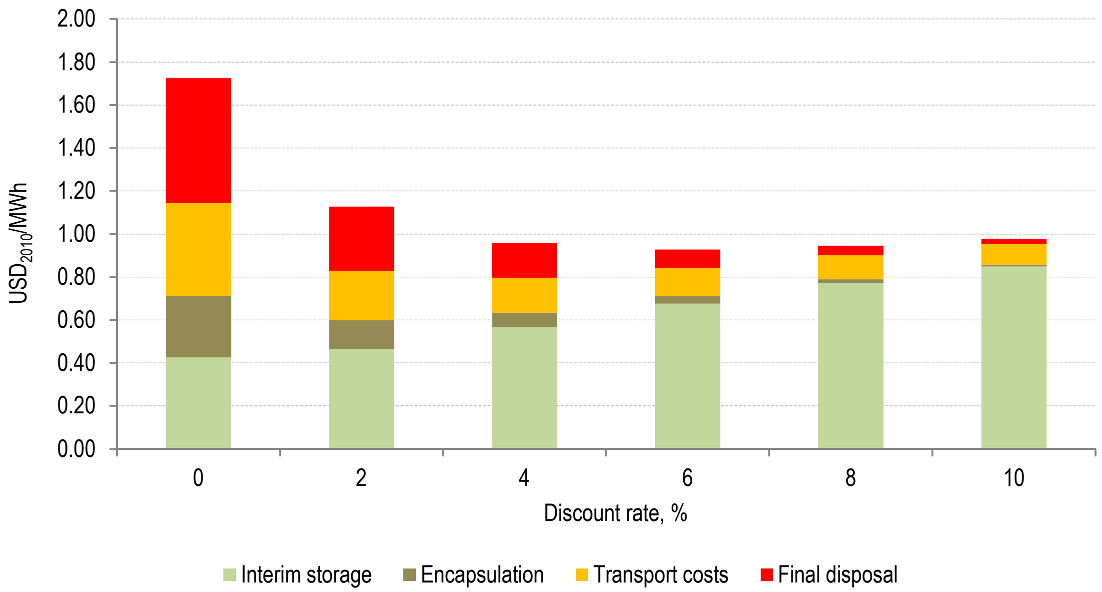


Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

One can observe that the introduction of non-zero discount rate of less than approximately 6% leads to decreased levelised costs for the back-end in the direct disposal strategy if compared to costs at 0%. In the direct disposal strategy, the largest investment corresponds to the deep geological repository that is constructed several decades after the first SNF assemblies are produced (see Figure 3.7), and it is operated after the end of electricity generation with NPPs. Thus, the contribution to the levelised cost decreases with increasing discount rate. However, the facilities that are constructed and operated during electricity generation show increasing contribution to the levelised cost for greater discount rates (see Figure 3.29). This is the reason why the strategy *multiple Pu recycling with LWRs and FRs* has levelised costs which increase with the discount rate (see Figure 3.29) – the contribution of the cost premium for FRs increases significantly with the discount rate. In the case of direct disposal strategy, the back-end costs start to (slightly) increase when the discount rate is sufficiently high (more than about 6%) and the contribution of the facilities operated during electricity generation, outweighs the discounting of the DGR cost.

Figure 3.29: Back-end cost breakdown for the direct disposal strategy at different discount rates

(Reference cost scenario, fleet generating 400 TWh/year)



As discussed in Section 3.2.5, for systems smaller than 400 TWh/year a centralised regional reprocessing plant is considered (located abroad), assumed to have a net capacity of 800 tHM/year and constructed with a fixed interest rate of 3%. For this reason, the reprocessing component in Figure 3.30 does not change with the discount rate.

Cost of fresh UOX fuel

The total cost of the nuclear fuel cycle strongly depends on the cost of the fresh UOX fuel (that in turns depends on the prices of natural uranium, conversion and enrichment services, and fuel fabrication costs).

Within the reference case assumptions on the uranium front end (summarised in Table 3.6), the cost of UOX is about USD_{2010} 2 810/kg, and the sensitivity of the UOX fuel cost to different individual cost components is given by the equation:

$$[\text{Cost of 1 kg of UOX }]= \left(\text{Cost}_{U_3O_8}+\text{Cost}_{\text{Conversion}}\right)\frac{e_{\text{fuel}}-e_{\text{tail}}}{e_{\text{nat}}-e_{\text{tail}}}+\text{Cost}_{\text{fuel fabrication}}+ N_{\text{SWU}}(e_{\text{fuel}},\ e_{\text{tail}})\cdot \text{Cost}_{\text{SWU}}$$

Using the enrichment and tailing rates from the reference case assumptions, one obtains N_{SWU}(4.95%, 0.25%) = 7.82 SWU/kg.

Figure 3.30: Back-end cost breakdown for multiple Pu recycling with LWRs and FRs strategy at different discount rates

(Reference cost scenario, fleet generating 400 TWh/year)

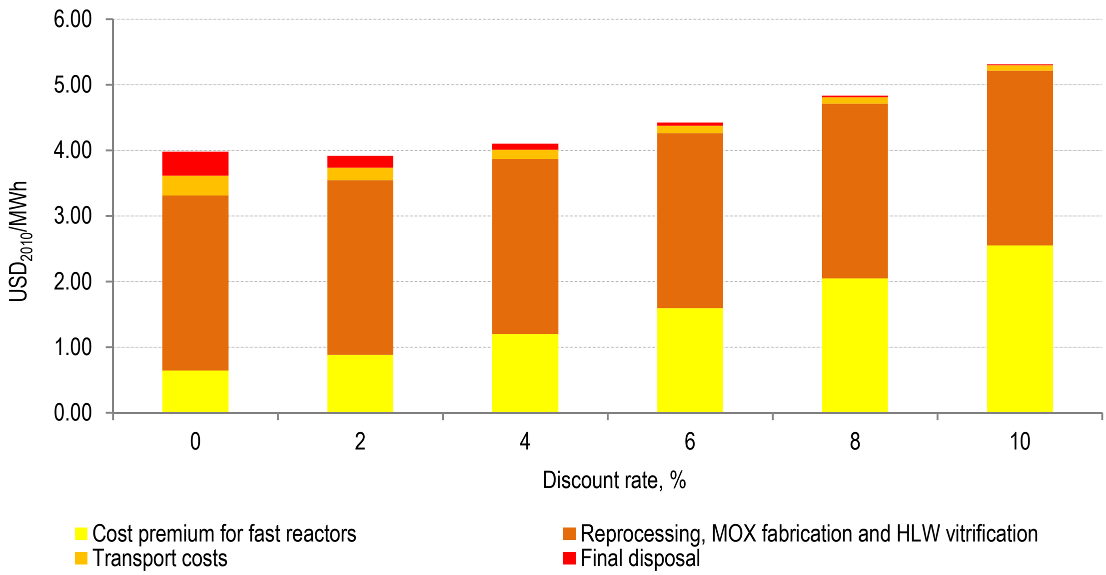
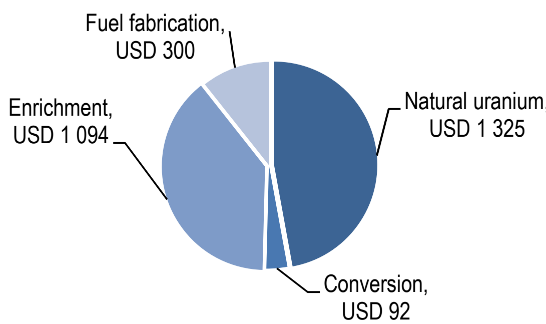


Table 3.6: Cost of UOX within the reference case assumptions

	Value	Unit
Natural uranium cost	130	USD per kgU
Conversion cost	9	USD per kgU
Enrichment cost	140	USD per SWU
Fuel fabrication cost for UOX and REPUOX	300	USD per kgU
Fuel enrichment	4.95%	Per cent
Fuel enrichment (REPUOX)	5.00%	Per cent
Enrichment tailings	0.25%	Per cent
U-235 content in the spent fuel	1.00%	Per cent

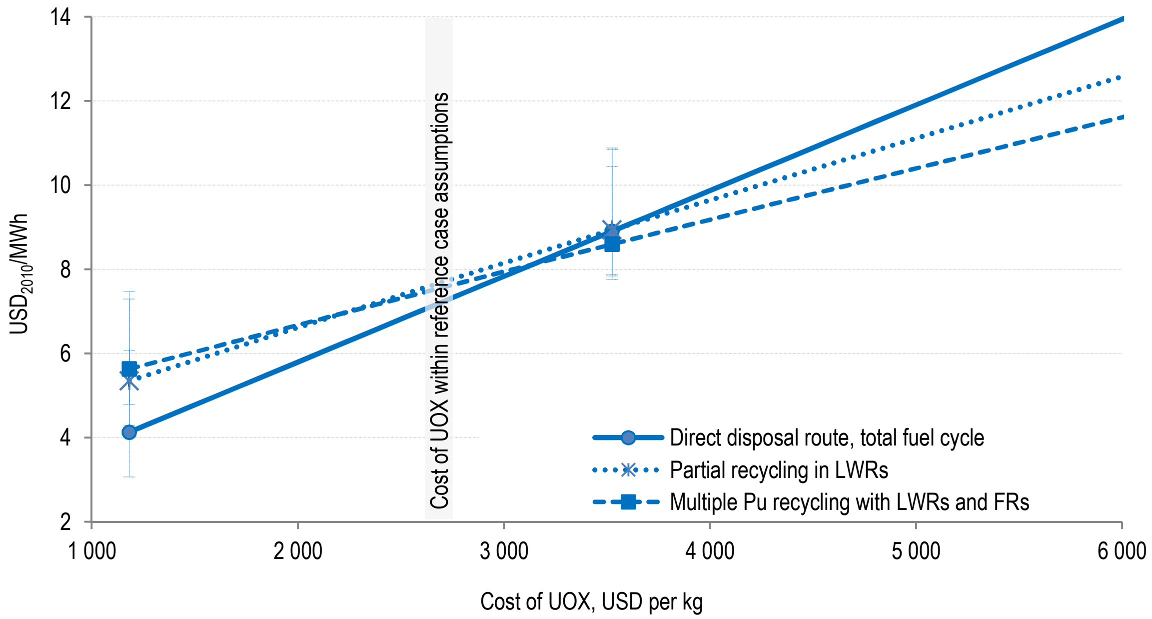
Cost of UOX in reference case (USD_{2010} per kg of UOX)



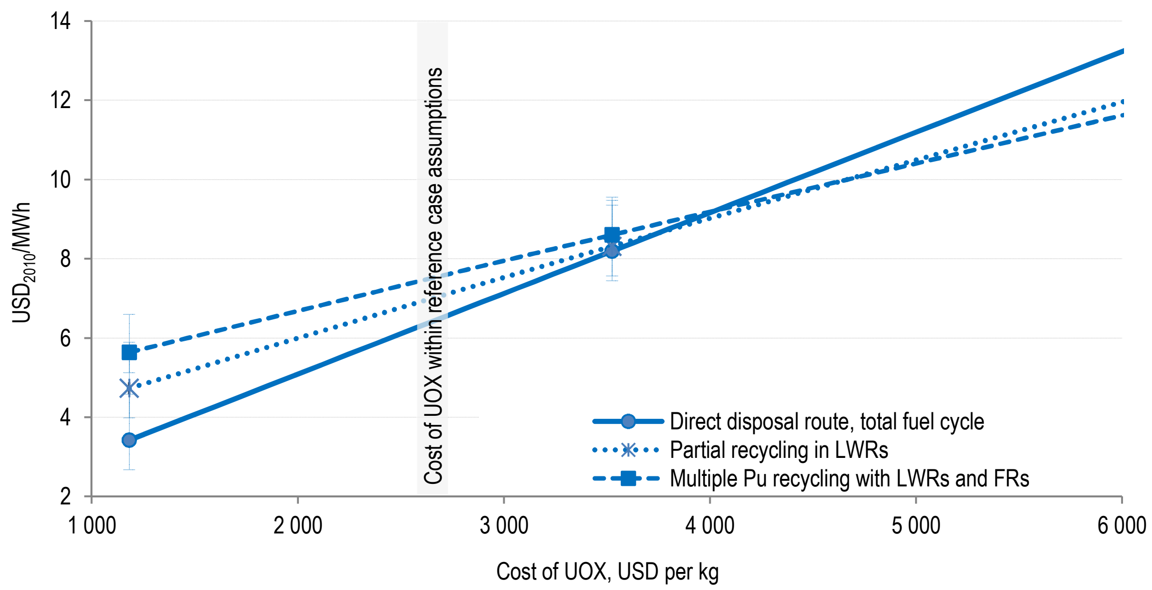
In Figure 3.31, the total fuel cycle costs for different back-end strategies are presented as a function of the cost of fresh UOX and for 0% and 3% discount rates. Given the uncertainty on the calculated costs, the three strategies can be considered comparable for a wide range of UOX costs.

Figure 3.31: Fuel cycle costs for a 400 TWh/year system for different back-end strategies as a function of fresh UOX cost

(0% discount rates)



(3% discount rates)



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

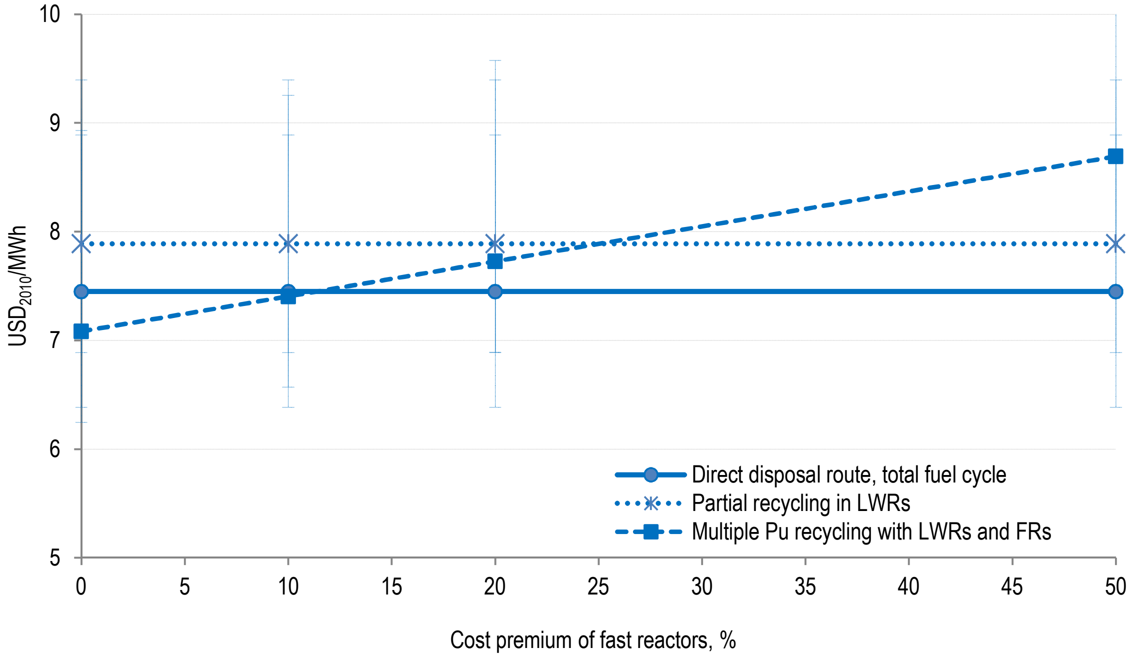
However, as an indication, the results corresponding to the reference case scenario at 0% discount rate suggest that, in a 400 TWh/year system, *multiple Pu recycling in LWRs and FRs* would have the lowest fuel cycle cost if the cost of fresh UOX was higher than approximately USD 3 200/kg_{UOX}. This corresponds to a level of prices of natural uranium of about USD 170/kgU (if the cost of enrichment, conversion and fuel fabrication are fixed) i.e. about 30% higher than the reference UOX cost assumption (see Table 3.6).

However, for the same size of system of 400 TWh/year and at 3% discount rate, the *multiple Pu recycling in LWRs and FRs* would become attractive if the cost of fresh UOX were ~50% higher than in the reference case scenario, corresponding to the level of prices of natural uranium of about USD 270-300/kgU (if the cost of enrichment, conversion and fuel fabrication are fixed) i.e. more than 100% higher than the reference assumption on the cost of natural uranium defined in Table 3.6.

Cost premium for fast reactors

The impact of the cost premium for fast reactors on the total fuel cycle costs for different back-end strategies is presented in Figure 3.32, for a 400 TWh/year system and for 0% discount rate. It is difficult to draw firm conclusions, due to the large uncertainty on the input data and hence the results derived. However, for a 400 TWh/year system, results obtained for the values corresponding to the reference cost scenario suggest that *multiple Pu recycling in LWRs and FRs* would be more economical than direct disposal if the cost premium for FRs were smaller than ~10%; and smaller than ~25% if compared to *partial recycling in LWRs*.

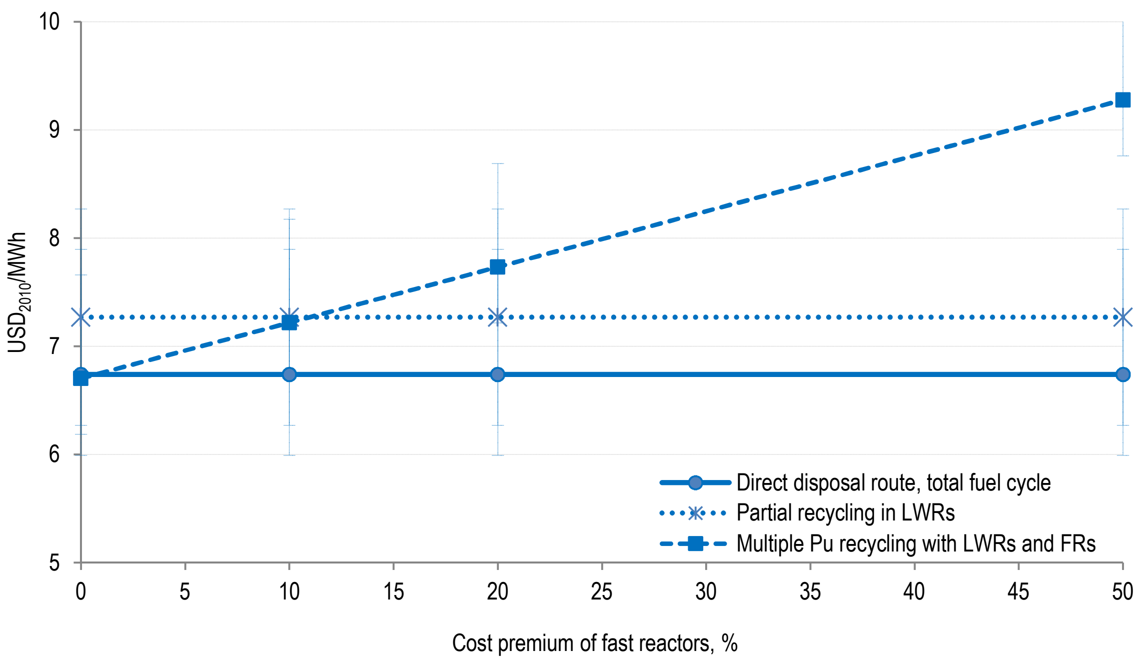
Figure 3.32: Fuel cycle costs for a 400 TWh/year system for different back-end strategies as a function of cost premium for FRs, 0% discount rate



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

For illustrative purposes, Figure 3.33 shows the calculated impact of the FR cost premium on the total fuel cycle costs at 3% discount rate. According to these results (for a 400 TWh/year system and reference cost scenario), *multiple Pu recycling in LWRs and FRs* and *direct disposal route* would have comparable total fuel cycle cost if the cost premium for FRs is zero (i.e. if FRs and LWRs have comparable capital and operating costs), and *multiple Pu recycling in LWRs and FRs* would be more economical than *partial recycling in LWRs* if the cost premium was less than ~10%. However, as for the case of 0% discount rate (Figure 3.32), the results are affected by large uncertainties that prevent the formulation of firm conclusions. In addition, the use of the same discount rate for all back-end facilities is a very strong assumption. Thus, a prudent conclusion from this analysis is that unless the cost premium of fast reactors becomes excessive there is no economic reason not to continue with their development.

Figure 3.33: Fuel cycle costs for a 400 TWh/year system for different back-end strategies as a function of cost premium for FRs, 3% discount rate



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

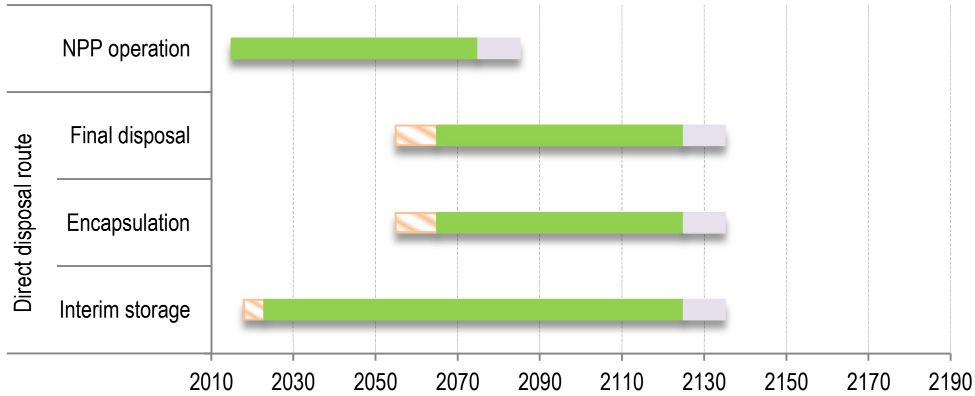
Sensitivity to the schedule of implementation

The sensitivity analysis with respect to the implementation schedule is performed for the *direct disposal of spent nuclear fuel* strategy using the following scenarios, see Figure 3.34:

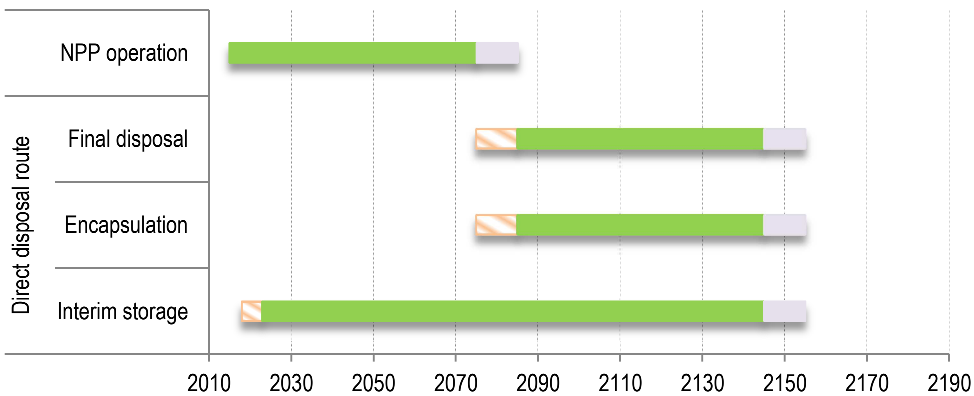
- The **timely implementation** schedule is the optimal case when all the facilities are constructed exactly at the time and in the period when they are required, with no delays.
- **20-year delay** in the construction of the SNF encapsulation facility and final disposal repository. The SNF stays longer in the interim storage.
- **50-year delay** in the construction of the SNF encapsulation facility and final disposal repository. The SNF stays longer in the interim storage.

Figure 3.34: Implementation schedules considered, direct disposal route

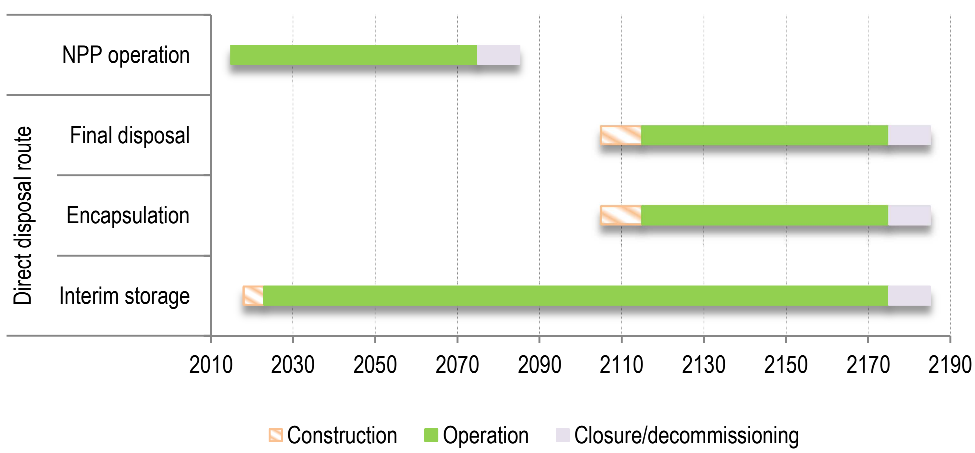
(Timely implementation)



(20-year delay)



(50-year delay)



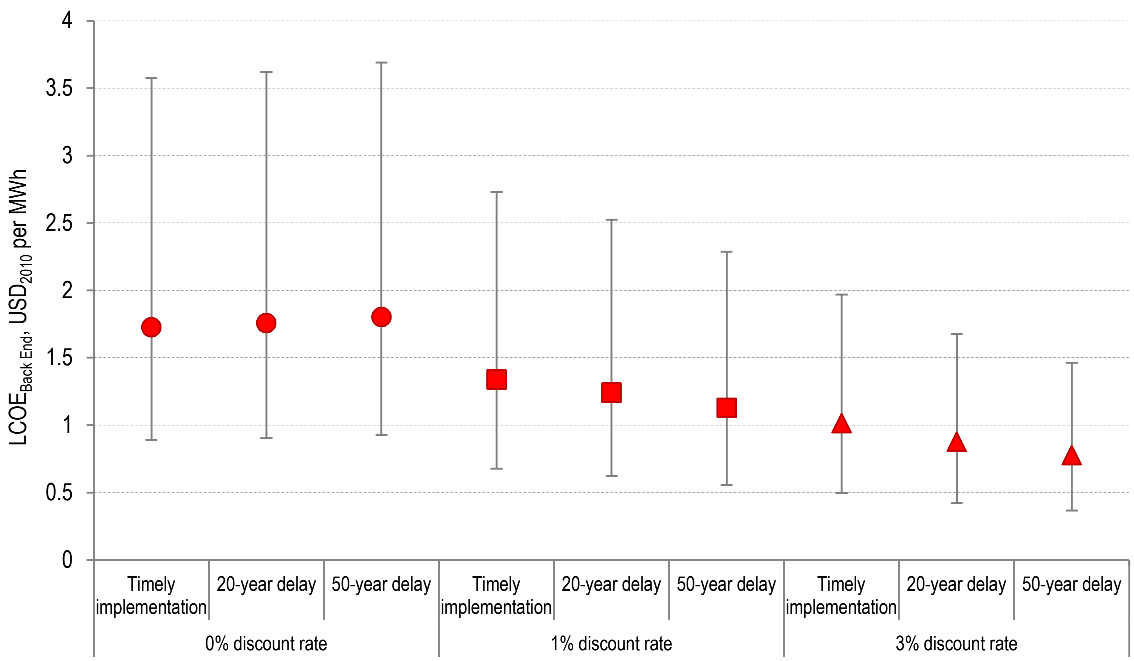
The impact of delays on the implementation of the direct disposal strategy in a 400 TWh is provided in Figure 3.35 at 0%, 1% and 3% discount rates.

Scenarios where delays in the implementation are postulated (which may also describe "wait-and-see" choices) lead to extended interim storage of the SNF, and thus the back-end component of the fuel cycle cost at zero discounts rate increases with delays. Because of discounting, scenarios with delays have smaller $LCOE_{Back\ end}$ at non-zero discount rates. The impact of delays is significantly smaller than the uncertainty on the back-end costs.

This simple analysis does not take into account the possible increased degradation of the SNF because of longer interim storage. This would lead to a further increase of undiscounted back-end costs.

Also, all calculations presented in Section 3.2 have been performed assuming that all nuclear reactors operate for 60 years. It would be useful, through further analyses, to assess impact of shortened reactor lifetimes (e.g. in the case of anticipated phase out or other unfavourable developments). Obviously, if the NPPs operational lifetime is reduced, the share of the back-end cost in the levelised cost of electricity increases.

Figure 3.35: Impact of the delays of implementation for a 400 TWh/year system, at 0%, 1% and 3% discount rates



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

3.3. Overview and comparison of existing studies on the economics of the back end

In this section a brief review of selected studies on the economics of the back end of the nuclear fuel cycle is presented. This review provides a comparative analysis of the various models, in terms of their calculation methods, assumptions, parameters and outcomes.

The list of studies included in the review is provided in Table 3.7. These fuel cycle studies were used to support specific economic analyses conducted for governments, universities, international institutions, and fuel service vendors.

Table 3.7: List of models considered for comparison

Short title*	Description	Comparison of back-end processes for fuel cycle studies					Modelling environment
		Direct disposal	Reprocessing and recycling	Multiple recycling	Fast reactors	Partitioning and transmutation	
AFCI** (2009)	**Advanced Fuel Cycle Initiative** (Dixon, B., *et al.*, 2008 and Shropshire D.E., *et al.*, 2009)	✓	✓	✓	✓	✓	Static, dynamic
MIT (2011)	**MIT Nuclear Fuel Cycle Study** (De Roo and Parsons, 2011)	✓	✓	✓	✓		Pseudo-dynamic
NEA (1994)	**The Economics of the Nuclear Fuel Cycle** (NEA, 1994)	✓	✓				Static
NEA (2006)	**Advanced Nuclear Fuel Cycles and Radioactive Waste Management** (NEA, 2006)	✓	✓	✓	✓	✓	Static
Rothwell (2011)	**The Value of Spent Nuclear Fuel Retrievability** (Rothwell, G., *et al.*, 2011)	✓	✓				Static
Harvard (2003)	**The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel** (Bunn, M., *et al.*, 2003)	✓	✓	✓	✓		Static
BCG (2006)	**Economic Assessment of Used Nuclear Fuel Management in the United States** (BCG, 2006)	✓	✓				Static
Oxford (2011)	**Economic assessment of used and spent nuclear fuel management in the United Kingdom** (Oxford, 2011)	✓	✓				Static

* These short titles are introduced to denote the studies listed in the adjacent column, and are used in the remainder of this chapter and in Appendix 6.

** Advanced Fuel Cycle Initiative.

The inputs and assumptions used in the models were specific to the objectives of the study. The models are generally used to compare the once-through cycle to various closed fuel cycles. The type of closed fuel cycle and the assumptions used varied greatly due to specific requirements of the country, technology developer, or research objective. Under these conditions, the models produced outputs that were specific to the study requirements. This section seeks to summarise the modelling differences (i.e. calculations, inherent assumptions) and to develop an understanding of the areas and depth of potential modelling uncertainty.

Back-end cost estimates are influenced by differences in assumptions (e.g. economic conditions, system performance, definitions of the final waste, etc.), costing and modelling methodological differences, input cost data and uncertainty. The general approach used in the studies considered in this review is similar and generally includes the following modelling assumptions:

- Material balances that work backwards or forwards from the reactor's annual fuel requirements.
- Constant dollar costing (unit costs do not change with time).
- Annual fuel cycle flow rates remain constant over the life of the facility.
- Unit costs for each of the major steps of the fuel cycle. In some studies, these costs are derived from the fuel cycle facility overnight investment costs, operation and maintenance costs. In other cases they are estimated theoretically.
- The typical outcome is specific, and levelised fuel cycle costs (e.g. in USD per MWh) are generally provided.

However, the studies were prepared from different perspectives due to different country fuel cycle policies related to issues such as reprocessing, waste regulations and classifications, and disposition plans for used fuel. Some differences between the studies include:

- A variety of different closed fuel cycle strategies depending on the overriding objective for uranium resource extension, waste management benefit, etc. Each of the studies addresses various elements of the back end of the nuclear fuel cycle. A snapshot of the areas addressed by the studies is provided in Table 3.7.
- The type of model, for instance static spreadsheet models, dynamic analysis of non-equilibrium and growth scenarios.
- Differing objectives, placing greater emphasis on a fuel cycle cost aspect (in particular for the legacy waste) or placing more emphasis on non-economic aspects (e.g. non-proliferation, security of supply, legal and regulatory aspects, and transport).
- Use of different categories of waste.
- Some models contain fewer cost details for conditioning, storage, and packaging of various waste streams in the advanced fuel cycles (e.g. separate unit costs for long-term storage of Americium (Am) and Curium (Cm) vs. U/TRU and U/Pu).
- Different methods (as a one-time and recurring annual cost) for calculation of dry storage costs.
- Combining product treatment/conditioning in the recycling cost and using separate unit costs for dry storage and packaging.

3.3.1. Summary of assumptions in the models considered

The assumptions used in the studies considered that are important to the calculated costs are summarised in Table 3.8.

The economic input data used in the model calculations are key to the modelling results. The nominal cost inputs used in the models for the fuel cycle front end (uranium, conversion, enrichment, fabrication, depleted uranium disposal), back end (fuel storage and disposal, HLW disposal) and recycling (product storage, reprocessing, MOX and TRU fuel fabrication) are provided in Table 3.9. The unit cost data were converted to USD of the year 2010 using a GDP deflator.[24]

24. Non-normalised values are provided in Appendix 6.

Table 3.8: Assumption differences between studies listed in Table 3.7

Assumptions	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	BCG (2006)	Oxford (2011)
Economic								
Cost escalation parity factor (year 2011 = 100%)	105%	100%	175%	119%	100%	139%	119%	100%
Discount rate	7.5%	7.6%	0-15%	6-12%	3%	2-8%	2-4%	2.5-3.5%
Fast reactor cost premium	+20%	+20%	N/A	+20%	N/A	+11%	N/A	N/A
MOX price discount (c/f U fuel)	0	0	0	0	N/A	N/A	15-25%	0-20%
Performance								
Efficiency - LWR - FR	 34% 38%	 33% 41%	 32% N/A	 34.11% 40.27%	 33% N/A	 33% 38%	 N/A N/A	 N/A N/A
Burn-up: GWD/tHM - UOX - MOX - Fast reactor	 51 N/A 131.9	 50 N/A 73	 42.5 48 N/A	 60 60 140	N/A	 43 43 84	 50 N/A N/A	N/A
FR conversion ratio (CR)	0.5 Burner	0.5-1.0-1.23 Burner to breeder	N/A	0.5 Burner	N/A	1.125 Breeder	N/A	N/A
Fleet: %LWR/%FR - Twice-through - Adv. fuel cycle	 N/A 75/25%	N/A	N/A	 63/37% 75/25%	N/A	N/A	N/A	N/A
Recycling technology basis	UREX+ EChem	PUREX+, UREX, TRUEX	PUREX	UREX, EChem, PUREX, ADS	PUREX+	PUREX+	COEX	PUREX+
Reprocessing capacity factor	66%	N/A		N/A	N/A	N/A	80%	N/A
Waste								
HLW form loading on repository	2.5	2.5	N/A	N/A	N/A	N/A	4.0 (no MOX SNF)	N/A
Used MOX management	Recycle in FRs	Recycle in FRs	MOX disposal	Recycle in FRs	MOX disposal	MOX Disposal	Storage, await FRs	MOX disposal

N/A = not applicable.

Table 3.9: Cost comparison between the fuel cycle unit costs in different studies

Fuel cycle description	Units	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	BCG (2006)	Oxford (2011)
		Nominal							Low-High
Front end									
Natural uranium	USD_{2010} per kgU	61	84	69	54	108	47	86	29.4-68.5
Conversion (natural)	USD_{2010} per SWU	10	10	11	5	11	7	13	9.8-29.4
Enrichment (natural)	USD_{2010} per kgU	107	167	153	108	127	118	118	98-176
UOX fuel fabrication	USD_{2010} per kgU	245	261	382	269	269	295	215	147-294
Depleted uranium disposition	USD_{2010} per kgU	10	10			6	7		
Back end									
Interim dry storage UOX	USD_{2010} per kgHM	123	209	208	161		236	161	
Geological disposal of spent UOX	USD_{2010} per kgHM	1 022	491	848	656*	220	472	753	396-1 982
Geological disposal of spent MOX	USD_{2010} per kgHM		3 270			920		2 408	
Geological disposal of reprocessed waste	USD_{2010} per kgHM			125	97*		236		
Geological repository (HLW FPs + Ln + Tc)**	USD_{2010} per kgFP	1 022	3 270						
Recycling									
Recycled U/TRU product storage	USD_{2010} per kgHM	204			323				
UOX reprocessing	USD_{2010} per kgHM	1 022	4 179	1 001	1 075	2 446	1 179	677***	
LWR MOX fuel fabrication	USD_{2010} per kgHM	1 993	2 508	1 362	1 344	2 643	1 769		
Fabrication of FR metal fuel	USD_{2010} per kgHM	2 555	2 508		2 795		2 063		

* 1991 data.

** Ln = Lanthanum; Tc = Technetium.

*** Cost of integrated plant in USD per kgU.

3.3.2. Comparison of outcomes

A benchmarking review was conducted on eight existing studies (and associated cost models) for the calculation of the back end of the nuclear fuel cycle. The models were compared in terms of their calculation methods, assumptions, key input parameters and outputs. The study placed primary emphasis on the nuclear fuel cycle costs for the closed fuel cycle in comparison to direct used fuel disposal.

A synopsis of all the differences between the studies and models is very difficult, especially considering the differences in scenario definitions and various underlying assumptions. A summary of comparative unit fuel cycle costs normalised[25] to the year

25. A summary of non-normalised fuel cycle costs is provided in Appendix 6.

2010 is provided in Table 3.10 and Table 3.11.[26] Results, obtained in Section 3.2, are also provided in Table 3.10 for comparison. One can generally derive a correlation between high fuel cycle costs for a fuel cycle strategy and key inputs (see Table 3.9 and Section 3.2) that may be driving the cost.

Table 3.10: Summary of modelling results

Results	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	*Results from Section 3.2, reference case, 3% discount rate*		
							System size		
							25 TWh/year	400 TWh/year	800 TWh/year
	Total FC/**back-end costs**								
Once-through, USD_{2010}/MWh	6.7/**2.7**	8.2/**1.3**	9.4/**1.3**	5.6/**1.7**	7.5/**1.1**	6.5/**2.1**	8.9/**3.2**	6.7/**1.0**	6.8/**0.9**
Twice-through, USD_{2010}/MWh	N/A	9.7/**2.8**	10.4/**2.6**	6.4/**N/A**	12.4/**6.7**	8.1/**3.8**	9.2/**4.6**	7.3/**2.7**	6.6/**2.1**
Adv. recycling, USD_{2010}/MWh	8.4/**6.0**	(10.3-11.3)/ **(3.3-4.3)**	N/A	7.0/**N/A**	N/A	9.2/**4.8**	8.9/**5.2**	7.7/**4.0**	7.0/**3.3**
FC cost premium for closed fuel cycle	26%	18-37%	14%	14%-25%	66%	25-42%	20%		

N/A = not applicable.

Table 3.11: Summary of modelling results for BCG (2006) and Oxford (2011)

Results	BCG (2006)	Oxford (2011)
	Back-end costs	
Once-through	USD_{2010} 582/ kgHM	#1 – GBP_{2011} 2 515 M (net present cost)
Twice-through	USD_{2010} 606/ kgHM	#2 – GBP_{2011} 1 812 M (net present cost)
Adv. recycling	N/A	N/A
FC cost premium for closed fuel cycle	4%	-28%
FR fuel fabrication	N/A	N/A

N/A = not applicable.

The following general observations could be made from this analysis:

- The results of modelling obtained in Section 3.2 are generally comparable to the results of other studies. However, the results are highly sensitive to the size of the system, discount rate and the input data. The role and impact of different parameters is discussed in Section 3.2.6.
- One of the major back-end fuel cycle cost factors in the open fuel cycle is geological disposal. According to the analysis presented in Section 3.2.7, the cost of interim storage becomes significant at larger discount rates (see Figure 3.29, for example).

26. The first six studies have comparable fuel cycle costs (Table 3.10); however the Oxford and BCG studies (Table 3.11) use different units and are difficult to compare to the other studies.

- For closed fuel cycles (twice-through and advanced cycles) the major cost factors are fuel reprocessing, HLW disposal, MOX and FR fuel fabrication, and waste conditioning processes. For closed cycles, the waste conditioning (e.g. vitrification) determines the loading of the HLW form (which can range from two to ten times relative to SNF loading). The radioactive constituents remaining in the waste coupled to the waste-loading factor, significantly impact the required size of the geological repository.
- Uncertainties about the costs of different back-end technologies in the studies reviewed are significant. An illustration of uncertainties (derived from AFCI [2009]) is provided for two closed fuel cycle systems, in Table 3.12. Comparable or even larger uncertainties have been identified in Sections 3.2.5-3.2.7. However, as noted in Section 3.2.7, the effects of these uncertainties are rather small on the fuel cycle cost.

Table 3.12: Illustration of cost uncertainties for back-end fuel cycle technologies

(based on AFCI [2009])

Fuel cycle technology	Fuel cycle cost	Cost uncertainty range
UREX+ separation	USD 1.5/MWh	± USD 1.00/MWh
Electrochemical separation/metal fuel fab	USD 1.5/MWh	± USD 0.75/MWh
HLW repository	USD 1.0/MWh	± USD 0.50/MWh
HLW/ILW/LLW conditioning	USD 0.8/MWh	± USD 0.40/MWh
MOX fuel fabrication	USD 0.5/MWh	± USD 0.25/MWh
Managed decay storage (Cs/Sr)	USD 0.4/MWh	± USD 0.20/MWh

Cs = Cesium; Sr = Strontium.

- For the majority of the twice-through fuel cycle studies (MIT, 2011; NEA, 1994 and 2006; and Harvard, 2003), the fuel cycle cost premium for using a MOX closed fuel cycle ranged from 14-25% over the cost of a once-through cycle using direct disposal. It is notable that in the BCG study the costs for closing the fuel cycle were only 4% higher than the cost of direct disposal. The two other extremes included:
  - Oxford (2011) estimated that, given the conditions in the United Kingdom, reprocessing legacy Pu and used fuel results in costs 28% lower than for direct disposal. This result is not surprising since the cost of reprocessing is not included in the analysis and the Pu is already separated.
  - Rothwell, G., *et al.* (2011) estimated that the twice-through costs are 66% higher than for direct disposal.
- Based on the findings for the advanced fuel cycles (AFCI, 2009; MIT, 2011; NEA, 2006; and Harvard, 2003); the fuel cycle cost premium for using a fast reactor closed fuel cycle ranges from 25-42% over the cost of the once-through cycle. Additional costs resulting from any cost premium on fast reactors would also need to be factored into the costs of using advanced fuel cycles. Also, country-specific requirements as well as the recycling technology maturity should be considered when defining the appropriate fuel cycle costs that are applicable to their situations.

References

BCG (2006), *Economic Assessment of Used Fuel Management in the United States*, Boston Consulting Group report, Boston, United States. Available at: www.bcg.fr/documents/file15203.pdf.

Bunn, M., *et al.* (2003), *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, DE-FG26-99FT4028, Cambridge, MA, United States.

Cour des Comptes (2012), *The Costs of the Nuclear Power Sector*, Paris, France. Available at: www.ccomptes.fr/content/download/43709/697228/version/2/file/thematic_public_report_costs_nuclear_+power_sector_012012.pdf.

De Roo, G. and J. Parsons (2011), "A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling", MIT Nuclear Fuel Cycle Study, *Energy Economics,* Vol. 33, pp. 826-839.

Dixon, B., *et al.* (2008), "Dynamic systems analysis report on nuclear fuel recycle", Advanced Fuel Cycle Initiative, Revision 1, INL/EXT-08-15201, AFCI-SYSA-AI-SS-RT-2009-0000053, December 2008.

DOE (2008), *Analysis of the Total System Life Cycle Cost of the Civilian Radwaste Management Program*, DOE/RW-0591, US Department of Energy, Washington, DC, United States.

DOE (2013), *U.S. Department of Energy Nuclear Waste Fund Fee Adequacy Assessment Report,* U.S. Department of Energy, Washington, D.C., United States. Available at: http://energy.gov/sites/prod/files/January%2016%202013%20Secretarial%20Determination%20of%20the%20Adequacy%20of%20the%20Nuclear%20Waste%20Fund%20Fee.pdf.

IEA/NEA (2010), *Projected Costs of Generating Electricity: 2010 Edition*, International Energy Agency and Nuclear Energy Agency, OECD Paris, France.

Meade, T. and M.H. Schwartz (2011), "The well-balanced market", *Nuclear Engineering International*, September issue, 2011, pp. 33-36. Available at: www.neimagazine.com/story.asp?storyCode=2060841.

NEA (1994), *The Economics of the Nuclear Fuel Cycle*, Nuclear Energy Agency, OECD, Paris, France.

NEA (2002), *Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles*, Nuclear Energy Agency, OECD Paris, France. Available at: www.oecd-nea.org/ndd/reports/2002/nea3109.html.

NEA (2006), *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, Nuclear Energy Agency, OECD, Paris, France.

NEA (2011), *Trends towards Sustainability in the Nuclear Fuel Cycle*, Nuclear Energy Agency, OECD, Paris, France.

NEA/IAEA (2011), *Uranium 2011: Resources, Production and Demand*, Nuclear Energy Agency, OECD, Paris, France.

ORNL (2007), *Analysis of the Reuse of Uranium Recovered from the Reprocessing of Commercial LWR Spent Fuel*, Oak Ridge National Laboratory report ORNL/TM-2007/207, Available at: http://info.ornl.gov/sites/publications/files/Pub14204.pdf.

ORNL (2011), *Decay Heat Calculations for PWR and BWR Assemblies Fueled with Uranium and Plutonium Mixed Oxide Fuel Using Scale*, Oak Ridge National Laboratory report ORNL/TM-2011/290, Available at: http://info.ornl.gov/sites/publications/files/Pub31857.pdf.

Oxford (2011), *A Low Carbon Nuclear Future: Economic Assessment of Nuclear Materials and Spent Nuclear Fuel Management in the UK*, Smith School of Enterprise and the Environment, March, Oxford, United Kingdom.

Peters, M., *et al.* (2002), *Plant Design and Economics for Chemical Engineers*, McGraw-Hill Science/Engineering/Math, 5th edition.

Rothwell, G., *et al.* (2011), "Option values for the long-term use of MOX", a working paper submitted to Energy Policy for the International Atomic Energy Agency, Vienna, Austria.

Shropshire D.E., *et al.* (2009), "Advanced fuel cycle cost basis 2009", Idaho National Laboratory report INL/EXT-07-12107 Rev. 2., United States. Available at: www.inl.gov/technicalpublications/Documents/4536700.pdf.

Chapter 4. Other factors influencing back-end options

4.1. Introduction

Any review of the back end of nuclear fuel cycles needs to acknowledge that economic factors alone, like costs of management and disposal of SNF and radwaste, are not sufficient to evaluate the comparative advantage of various fuel cycle options. To better inform sociopolitical decisions in this area, the basis for any comprehensive evaluation has to be broadened through an assessment of the impact of additional factors. In some respects, these factors may be of key importance for the comparative evaluation and selection of fuel cycles. However, they tend to be highly dependent on specific national situations and can neither be generally quantified nor ranked in their importance.

This chapter discusses – in a general way – a number of these qualitative factors. Some of them have a strong political weight and belong to the governmental sphere, some relate to social issues, while others are of a more technical nature.

The qualitative factors analysed are:

- security of energy supply;
- non-proliferation;
- public attitudes;
- environmental effects;
- waste streams;
- transport;
- development of fast reactors and advanced fuel cycles;
- retrievability of waste;
- legal, regulatory aspects;
- safety aspects.

For each of these qualitative factors, the most important features that may directly impact on the performance of the back end of the open fuel cycle and fuel cycles with reprocessing are considered. As far as practicable, their potential impacts on policy, economic or societal issues that they may have on one or the other fuel cycle option is analysed. A short section at the end of this chapter sums up the finding of this analysis.

4.2. Security of energy supply

Security of energy supply can be defined (NEA, 2010) as the resilience of an energy system to unique and unforeseeable events that threaten the physical integrity of energy flows or that lead to discontinuous price rises (independent of economic fundamentals). Security of energy supply is a key driver for developed and developing societies, their well-functioning and well-being and their economies. As security of supply constitutes a fundamental issue for governments, these are generally prepared to take action to maintain or improve it. In defining energy policies, governments need to ensure security of energy supply that is economically affordable and generates only low carbon emissions.

To address the role of nuclear power in assuring security of supply, two types of risks need to be considered:

- external, or geopolitical;
- internal risks.

4.2.1. Geopolitical risks

The open fuel cycle or FCs with partial recycling rely dominantly on natural uranium as the primary resource, which is produced in disparate, generally stable countries. Geopolitical risks, however, may still arise, in particular from less diversified front-end services (e.g. enrichment) and potential failures of international markets where these resources are traded. The most effective means of mitigating geopolitical risks from the disruption of supply of primary resources are diversification of supply, the establishment of strategic reserves and well-functioning markets.

Current nuclear fuel cycles have already achieved a measurable increase of the energy supply security, as can be gathered from the historical evolution of the Simplified Supply and Demand Index (NEA, 2010). This can be attributed to several factors and, in particular, to the quantity and geographical distribution of uranium reserves, as well as the robust markets existing for uranium mining and enrichment:

Uranium resources and actual extraction have a diversified distribution and come principally from stable countries. Uranium mining and enrichment have a large production base in NEA countries. Furthermore, uranium has lower exhaustion risk as compared to fossil fuels such as oil (NEA, 2008). "Secondary supplies", e.g. down blending highly enriched uranium from nuclear warheads, stocks held by governments or utilities and recycled materials, have also been available and widely exploited in the past; however historic secondary uranium stocks are expected to decline.[1] Additional secondary supplies can be obtained from more unconventional sources like recovery from phosphates; there is also a considerable quantity of uranium in black shales, while uranium recovery from coal and coal ash is under consideration (NEA, 2011a). Albeit a more remote perspective, recovery from seawater is also considered and under development.

The international uranium market is almost entirely based on long-term contracts (for example, in 2011 the ratio of spot to total deliveries of natural uranium to EU facilities was only 4% (Euratom, 2011).

Uranium is easily storable because of its high energy density (the energy content of 1 tonne of uranium used in LWRs is equivalent to the energy content of 14 000 to 23 000 tonnes of coal [NEA, 2008]), and does not pose a significant financial burden to the storing entity.

The long fuel service time in the reactor core, together with the large amount of fuel material "stored" in the fabrication pipeline, makes nuclear power production relatively resilient to uranium supply disruptions. Current LWRs operate without refuelling for 12-18 months, and, upon delayed deliveries of fresh fuel, coastdowns are a possibility, allowing the reactor to extend its operations for a few additional months, albeit at reduced power.

The cost of nuclear-produced electricity is largely stable and uranium price changes have lower impact on it in comparison with, e.g. fuel for fossil energy sources.

1. In 2013, the HEU disposition agreement between the governments of the United States and the Russian Federation will expire.

In case even higher levels of security of supply were required, the need for primary material and thus the external risks can be further reduced (approximately by 15%) by making better use of the energy content of the nuclear fuel through the adoption of reprocessing and MOX utilisation; or, much more considerably, by introducing fissile breeding and fully closed fuel cycles. Less than 1% of the energy content of the mined uranium is used in the current open fuel cycle. With the necessary infrastructure for separation, re-fabrication, re-enrichment and irradiation in place, a higher energy fraction can be extracted even in the current LWR fleet with the use of discharged plutonium in MOX fuel and use of reprocessed uranium. However, to compensate for the presence of ^{236}U, the reprocessed uranium would need to be enriched to a slightly higher level than standard enriched uranium fuel.

Virtually the entire energy content (minus the processing losses) of ^{238}U and of the other actinides could be extracted in FCs which involve fast reactors, featuring a fissile conversion ratio higher than one and capable of burning minor actinides. However, this would require the development of fast reactors at a commercial scale and a substantial transformation of the current fuel cycle infrastructure and additional facilities capable of handling fast reactor fuel ("hotter" and more radiotoxic).

4.2.2. Internal risks due to technical, economical and safety performance

Internal risks include technical, financial and economic risks that may stem from technical performance or safety issues or from severe failures of markets providing the services needed to convert primary or reprocessed material into fuel.

The deployment of energy infrastructure including reprocessing and advanced fuel cycle facilities depends predominantly on technological (besides political and economic) constraints rather than on primary materials and thus, in principle, it can be pursued within the consuming countries to reduce or eliminate geopolitical risks, shifting these from external risks to risks internal to the fuel cycle.

Contrary to uranium mines, the siting of which cannot be chosen, these facilities can also be located in political stable and market-oriented regions, thus promoting well-functioning international markets for their respective services.

Another internal risk is related to the safety of nuclear facilities worldwide, including back-end facilities such as spent fuel handling, storage, reprocessing and final disposal. Safety is essential for maintaining and enhancing the security of energy supply provided by nuclear energy. Accidents, including those outside of a countries' national border, may lead to public and political pressures that can significantly affect nuclear policies in an adverse manner, thus possibly reducing the positive contribution of nuclear energy to the overall security of energy supply. Safety aspects are further discussed in Section 4.11.

The technical and local diversity of facilities and services, including a well-developed infrastructure for separation, re-fabrication, possibly re-enrichment and irradiation capabilities, broadens the resources and fosters competitive and functioning markets; hence it may have some added benefits for security of energy supply in the long term. However, the high-fixed costs of such installations will make this introduction challenging and likely to require substantial governmental support.

In general, well planned energy policies in NEA member countries are not purely based on full national energy independence but also seek good integration in well-functioning markets.

4.3. Non-proliferation

The international legal framework for preventing the spread of nuclear weapons and ensuring the security of nuclear materials and facilities has evolved over half a century. For about four decades the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) has been the legal and political keystone for preventing proliferation. The NPT is implemented by a comprehensive safeguards system, by which the IAEA, the world's "nuclear inspectorate", can verify that a country is complying with its commitments not to use its nuclear programme for nuclear weapon purposes. The NPT makes it mandatory to all non-nuclear-weapon states to conclude comprehensive safeguards agreements with the IAEA; an extensive set of technical measures that allow the IAEA Secretariat to independently verify the correctness and the completeness of the declarations made by states about their nuclear material and activities. The Additional Protocol (IAEA, 1998) strengthens the comprehensive safeguards agreement and allows the IAEA to draw safeguards conclusions also about the absence of undeclared nuclear material and activities (IAEA, 2012). This is increasingly being ratified by countries having nuclear programmes.

Notwithstanding these international control mechanisms, the inherent non-proliferation characteristics of specific nuclear facilities have consistently been of principal political concern in the choice of fuel cycle options. The political impact of non-proliferation considerations on civil FC policies became evident, when in 1980 the United States forwent civil reprocessing following the findings of an International Nuclear Fuel Cycle Evaluation (INFCE 1977-1980) (IAEA, 1980). This decision is still guiding the US position in its international stances.

While the global nuclear non-proliferation regime has worked effectively, some concerns have been recently raised i.e. in relation to non-nuclear-weapon states that have been found to be in non-compliance with their safeguards agreement, and the detection of burgeoning and alarmingly well organised nuclear supply networks. Furthermore, in the context of new or reawakened interest in nuclear energy in various regions of the world there is a potential for a greater number of states to consider developing their own fuel cycle facilities and nuclear know-how. Therefore, the last decade has seen an increased focus on proliferation resistance in order to minimise the attractiveness and vulnerability of nuclear materials and technology to a nuclear weapons programme. At the same time, proliferation resistance is often addressed in conjunction with physical protection as covering those measures required to avoid diversion of nuclear material by sub-national or terrorists groups.

4.3.1. Open fuel cycle

The back end of the open fuel cycle presents some inherent features which favour proliferation resistance. These include the strong self-protective radiation field of the SNF matrix where the fissile material is dispersed, which provides a mix of physical and chemical barriers; and the industrial scale of back-end facilities that increases the timescales needed to access the fissile material and hence the probability of early detection. So far, no country has proliferated by diverting materials or facilities under IAEA safeguards and little concern exists for the functioning of the current safeguards system for the back end of the open fuel cycle.

In comparison to above ground facilities, for which the IAEA has experience implementing safeguards monitoring and verification measures, geological repository safeguards present unique challenges for verifying the disposed material. Although a generic safeguards approach for geological repositories has been developed and generally accepted, safeguard measures and procedures have not been applied or tested under site-specific conditions. The IAEA expects that, with appropriate advanced planning, the operational and safety impacts of applying routine traditional IAEA safeguards in a geological repository will not be greater or technically more challenging than those affecting other types of nuclear facilities (IAEA, 2010).

Implementing retrievability into the design of a geological repository would not change the inherent proliferation resistance in principle. Regarding proliferation resistance, retrievable emplacement of nuclear material packages is comparable to maintaining the repository in its operational phase for the period of retrievability. During this period, physical security measures would continue to be required and the intrinsic barriers will still apply.

4.3.2. Reprocessing

For the conventional reprocessing option, which entails SNF reprocessing and the recycling of recovered fissile materials, the back end of the fuel cycle has historically been regarded as one of the key vulnerabilities, as this typically involves the separation of pure streams of uranium and plutonium and their eventual transportation and storage. The safeguarding of reprocessing is technically demanding but is being routinely implemented. A technical option to improve the proliferation resistance of reprocessing is the prompt recycling of the plutonium produced. This practice, pursued for instance by France, avoids the accumulation of large stocks of separated plutonium, while the plutonium remaining in discharged spent MOX is, like SNF, subject to a higher degree of self-protection from the radiation field (NEA, 2011a). However, there are limitations to this approach as even very prompt recycling of plutonium, within a few days or weeks, will unavoidably involve significant quantities of fissile material being accumulated at some point in the fuel cycle.[2]

By limiting the deployment of sensitive national facilities, market mechanisms that strengthen security of supply through multilateral approaches may contribute to further reduce the threat of proliferation.

In 2005, an IAEA expert group on Multilateral Approaches to the Nuclear Fuel Cycle (MNA) analysed the possibilities of strengthening markets, in particular for enrichment, reprocessing and disposal services, and, concurrently, their associated proliferation resistance, by protecting them from possible politically motivated interventions of national governments (IAEA, 2005). To this end, in the view of the MNA group, the following three types of mechanisms were identified as effective in rendering the fuel cycle more resilient against attempts of "rogue", non-compliant states to proliferate materials, knowledge and facilities towards use in weapon programmes:

- assurances of services not involving ownership of facilities;
- conversion of existing national facilities to multinational facilities;
- construction of new joint facilities.

Effective assurances of supply would have to include back-up sources of supply in the event that an MNA supplier is unable to provide the required material or services.

Specific non-proliferation questions may come up if a country decides to end an active reprocessing policy. To avoid important stockpiles of separated plutonium, plans must be made to use the separated plutonium or render it unusable. One way to do this is to produce MOX fuel elements to be burned during electricity generation in nuclear reactors.

4.3.3. Advanced fuel cycles

In the past 10 to 15 years, there have been developments, which have led to a renewal of interest in reprocessing and recycling in fast reactors. One of the key goals of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and

2. A significant quantity of plutonium is set by IAEA at 6 kg. Commercial reprocessing plants typically have capacities ranging from a few hundred tonnes of spent fuel per year to more than one thousand tonnes per year. Given that 1 tonne of LWR spent fuel can contain as much as 12 kg of plutonium, there is the potential to produce several significant quantities in just a single day of operation.

Generation IV International Forum (GIF) – two leading international projects whose objective is to promote the development of a new generation of advanced nuclear systems – is the enhancement of the inherent proliferation resistance and physical protection characteristics of such new system designs. This has led to international R&D into advanced reprocessing flow sheets, which are designed to ease proliferation concerns by avoiding the separation of pure plutonium streams (see also Section 2.3.2).

The introduction of fast breeder reactors opens up new aspects of proliferation risks and safeguards, as plutonium of good weapons quality would be generated in the blanket of the reactor.

4.4. Public attitudes

As discussed in Section 2.3.3, broad national political consensus and a favourable public attitude are of paramount importance for issues related to nuclear policies at large and, more specifically, back-end solutions. Section 2.3.3 considers some exemplar cases of new approaches and different achievements registered in various countries towards an improved public dialogue in the implementation of back-end strategies.

The potential for social conflict regarding siting, constructing and operating individual facilities seems to be largely dependent on local and regional issues. Balancing the impacts and benefits of hosting a nuclear facility on the current "well-being" and future development of the host community or region constitutes a key factor in reducing the potential for conflict. This balance can be better assessed for "production" facilities like NPPs, reprocessing plants or fuel manufacturing facilities than for waste disposal or centralised storage facilities. For the first type of facilities the benefits in terms of significant employment and revenues generated for the local and/or regional communities are more tangible and directly tied to the actual operation of the plant. For waste facilities, on the other hand, such benefits are less obvious and sometimes need to be generated via specific funding arrangements independent of the actual operation of the facility. This can pose issues of transparency and ultimately also trust. Further, the assessment of benefits and possible detriments is more reliable when data and experience from similar existing facilities, including non-nuclear ones, are already available. In these cases the public dialogue tends to be more rational and responsive to economic provisions. Conversely, public debate on geological disposal facilities typically tends to revolve around a much broader spectrum of values, including ethical aspects of undue burdens on future generations and safety over extremely long timeframes. For this reason, resolving social conflict and gaining public acceptance for SNF/HLW repositories – obtaining the so-called "social licence" – is an extremely complicated, time and resource consuming process.

Reducing the potential for social conflicts about implementing waste repositories and/or finally resolving them can be a very substantial cost. Associated costs can range from moderate sums to empower communities to build their own expertise (as in Sweden), up to several hundreds of USD millions. For instance, in the Republic of Korea, a sizeable support fund (of approximately USD 300 million) was provided to the region which hosted the LLW disposal site. In that instance, a regional development package comprised the establishment of R&D facilities and the relocation of the implementer's headquarters into the site region.

As international experience shows, public acceptance of DGR for SNF/HLW does not seem to be inherently influenced by the specific choice of the fuel cycle (whether open or twice-through). Both non-reprocessing countries like e.g. the United States as well as countries pursuing reprocessing and recycling like the United Kingdom, at some point in time have experienced severe failures in their efforts to site a DGR due to insufficient public support. Also in Germany, a country that changed its policy and effectively banned reprocessing in 2005, this decision did not substantially influence the public view on the Gorleben repository project. Given the complexity of reasons for civil society to oppose a planned DGR, there is some doubt that reducing the amount of very long-lived radioactivity in the waste as envisaged with the introduction of advanced fuel cycles will make a decisive difference for public acceptance (however, advanced fuel cycles will reduce substantially the amount of HLW to be disposed of and thus the size of a repository or the number of repositories needed in the long term).

Given the limited number of commercial reprocessing facilities, there is no clear indication of a specific factor affecting public attitudes towards the implementation of such facilities. While in Germany a project to construct a reprocessing facility (Wiederaufarbeitungsanlage Wackersdorf) was stopped (in 1989) very much due to civil protest, the construction of the Rokkasho reprocessing plant in Japan did not face comparable social conflict.

While, as further discussed in Section 2.3.3, there are several recent examples of positive public acceptance for disposal facilities (e.g. Finland, France and Sweden), interim storage facilities (i.e. the Netherlands and Spain) and LILW facilities (e.g. Belgium, Bulgaria, Lithuania, the United Kingdom and the United States), there are also multiple examples of siting processes or local consent for nuclear facilities failing by not addressing some of the stakeholder interests. The lack of public support can lead to substantial delays or, in the extreme case, even to the eventual abandonment of advanced waste repository programmes. This eventuality may result in the loss of virtually the entire investment, generating costs which can easily reach the order of multi-billion USD (as experienced in the United States for the Yucca Mountain project).

The process of gaining public acceptance on waste management should be science-informed, consent-based, open and transparent. As the Blue Ribbon Commission put it:

> "we know what we have to do, we know we have to do it, and we even know how to do it. (…) Rather the core difficulty remains what it has always been: (…) to conduct the waste management program in a manner that allows all stakeholders (…) to conclude that their interests have been adequately protected and their well-being enhanced – not merely sacrificed or overridden by the interests of the country as a whole" (BRC, 2012).

4.5. Environmental effects

4.5.1. Conventional environmental effects

Major industrial activities and in particular energy supply chains have the potential of generating environmental effects that can impact human health and can more generally degrade the environmental quality of the human habitat. Major repercussions associated with pollution from fossil fuels are global warming, generally thought to result from anthropogenic greenhouse gas (GHG) emissions, and significant deleterious health effects due to fine particulate emissions and other particulate and gaseous emissions.

The emissions of nuclear – and likewise renewables chains – are between one and two orders of magnitude below average GHG emissions of lignite, hard coal, oil and gas. Life cycle analyses of electricity production chains show that nuclear power, with low CO_2 emissions, is one of the most effective power production technologies for avoiding emissions-related health effects (NEA, 2008).

However, nuclear power production is not totally free of these conventional environmental impacts and different stages of the fuel cycle contribute differently to its overall environmental impact.

Uranium mining has the largest environmental footprint in the nuclear fuel cycle. Uranium mining is currently carried out using open-pit (around 23%), underground (around 32%) and *in situ* leach (ISL) (around 39%) extraction methods, as well as, to a lesser extent, co-product and by-product recovery from copper and gold operations (6%) (NEA/IAEA, 2012). Physical, chemical and environmental impacts resulting from these extraction processes are broadly similar to the extraction of other materials, with the exception of ISL mining. Modern application of ISL in suitable geologies reduces environmental impact through decreased surface disturbance and no generation of waste rock piles or tailings; and, if deployed under strict environmental control (regulation), ISL offers the possibility of simpler rehabilitation. By reusing part of the residual energy content of spent fuel and hence lessening natural uranium needs, recycling contributes to reducing the impact related to uranium mining.

Geological disposal of radioactive waste, while in some aspects comparable to a mining operation, has a much smaller conventional environmental impact as less volume is involved and the material brought to the surface is not processed and non-radioactive.

Nuclear power plants in themselves have a low environmental impact during normal operation. They have low emissions of chemically hazardous material, use relatively little land, their releases of radioactivity are low and they have no or very low direct releases of carbon dioxide or particulate matter. In common with most other industrial-scale means of generating power, including all fossil-fuelled and waste/bio-fuelled power plants, nuclear power plants will, however, result in discharges of thermal energy, e.g. water temperatures above average for the local environment (NEA, 2008). Like for all energy sources conventional environmental effects have to be considered for the whole life-cycle and process chain of all nuclear power related facilities. Radiological impacts and safety-related issues are discussed in Sections 4.5.2 and 4.11 respectively.

4.5.2. Releases of radioactive effluents

The radiological unit of collective dose, which measures the effect on the population as a whole rather than an individual's risk (and is thus related to total radioactivity release) is an appropriate measure to describe the overall radiological environmental impact of nuclear facilities. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates that radioactive effluents from all stages of nuclear power generation lead to collective doses of 0.72 manSv/GWa (man sievert per gigawatt-year) averaging over the currently worldwide-implemented fuel cycle policies and facilities. [3] The main contributors are mining and milling, reactor operation and reprocessing. Neither enrichment nor fuel fabrication give rise to large individual or collective doses, since releases to the environment are very low and most radioactive daughter products have been removed during the preceding steps of milling and refining. The radiological impact of these stages is estimated to be only about 0.003 man-Sv/GWa (UNSCEAR, 2008) and there is no indication that this may change with a larger use of MOX fuel. The collective dose due to low- and intermediate-level waste disposal is also very low (0.5 manSv/GWa) and geological repositories of spent fuel and high-level waste from reprocessing are being developed to ensure that only minor releases of radioactivity can occur even over long timeframes.

3. "The collective dose is the dose delivered integrally over very long time periods and to an assumed 'maximum' population of the world and provides a basis for comparison of the overall impact. The maximum annual per caput dose to the global population is estimated by UNSCEAR to be less than 0.2 microSV (μSv); this compares to the worldwide average natural dose to humans of about 2.4 millisievert (mSv) per year" (UNSCEAR, 2008).

Given the current mix of mining and extraction technologies, due to the emission of natural Radon, uranium mining and milling is the biggest contributor to the collective dose from nuclear power generation worldwide, together with the operation of NPPs. However, actual releases depend very much on the technology applied (open pit, underground mining or ISL) and the proper handling of tailings. Adequate remedial actions exist to reduce long-term radiological impacts caused by radon emissions from mining and milling tailing piles, but it seems difficult to further reduce the radon release during the operating phase of mining and milling.

The annual releases of radionuclides from NPPs have decreased dramatically since the early days of the industry and further sizeable reductions of effluents have been achieved since the early 1990s, corresponding, e.g. in France, to a factor of ten decrease in radioactivity of effluents from NPPs (Clavel, 2008). With modern practices, only noble gases and tritium (^{3}H) are discharged in measurable quantities. Learning from experience, better technology and the adoption of the goal to reduce doses as-low-as-reasonably-achievable (ALARA), have been the main factors which have driven continuous improvement in industry performance. The same drivers have also led to substantially lower discharges from reprocessing facilities since the 1970s to today, resulting in collective doses per unit of electricity generation being reduced by over two orders of magnitude (NEA, 2008). These achievements have also been fostered by a shift in the political attitude, giving increasing emphasis to environmental protection. Nevertheless, UNSCEAR estimates the collective dose due to releases from reprocessing as 0.11 manSv/GWa (UNSCEAR 2008), a significant part of the overall 0.72 manSv/GWa for the entire nuclear power generation. Concerns about the radiological environmental impact of reprocessing figure prominently in public opinion and policy making. In particular, past radioactive releases from some reprocessing plants influenced the decision of governments (e.g. in Germany and Sweden) to abandon the policy of SNF reprocessing.

Reprocessing clearly introduces an additional source of radiological environmental impact in comparison to the open fuel cycle (although, as noted above, continued industrial efforts towards process improvements have led to a sizeable reduction of effluent releases from reprocessing). This effect is partly offset by about 20% reduction in the need for fresh uranium fuel that translates into an equal reduction in discharges from uranium mining and milling operations. A study prepared for the OSPAR Commission (NEA, 2000) compared the radiological impact of the open fuel cycle with an FC involving (single) reprocessing based on actual data of specific reference facilities. The study confirmed the higher "face value" radiological impact of a fuel cycle with reprocessing, however noted the sensitivity of this result to assumptions of population distribution, release conditions and employment of best practice for the mining and milling operation. Given the uncertainties involved, the reprocessing of spent fuel may be seen essentially as "neutral" in terms of environmental and health impact, although it does result in a shift of radiological impacts from uranium mining areas to the vicinity of reprocessing plants. In a fully closed fuel cycle the reduction of uranium needs would be much larger and thus the effects discussed here would be much more pronounced.

4.6. Waste streams

In the fuel cycle radioactive waste are produced at all stages, ranging from very high activity materials like SNF or HLW from reprocessing to LILW-LL and LILW-SL down to VLLW e.g. from decommissioning. All this waste must be managed safely and in a manner that protects humans and their environment taking into account a broad and complex range of issues.

As discussed in Section 1.4, technologies and facilities for conditioning, storage and disposal of this waste exist, or – as for DGRs for HLW and SNF – are in advanced stages of development in some countries. However, open fuel cycles and reprocessing fuel cycles produce different waste streams within the various waste categories that may impact on a comparative evaluation of different fuel cycles. For example, HLW derives by and large from the fission product residue of reprocessing or the packaging of spent fuel for direct disposal. Low- and intermediate-level waste with long-lived radionuclides arise almost entirely from reprocessing (fuel cladding hulls, spacers, end-pieces and fines from the dissolution of spent nuclear fuel). Low-level waste and short-lived intermediate-level waste are generated at all stages.

The impact of open fuel cycles, reprocessing and advanced fuel cycles on HLW/SNF waste streams has been evaluated in several detailed studies (e.g. NEA, 2006; NEA, 2011a; DOE, 2008) and most recently in the report of the Blue Ribbon Commission on America's Nuclear Future (BRC, 2012a). With respect to deep geological disposal of HLW/SNF and LILW-LL, the long-term toxicity of the waste, the amount of waste and the repository space requirements are the most important criteria.

4.6.1. HLW/SNF

The long-term toxicity (after decay of the most active fission products) of HLW/SNF is determined by the transuranic isotopes (TRU) produced in the reactor. In the case of reprocessing, there is a reduction in the amount of transuranics being sent to the repository because fission reactions in the MOX fuel lead to a net destruction of transuranic elements compared to the once-through cycle. However, the reduction in long-term toxicity is relatively small and unlikely to be important in most disposal settings (BRC, 2012a).

Regarding the waste volume, an increase of the repository drift loading factor[4] by 2.5 is calculated for waste from reprocessing (including the LILW-LL) in comparison to the open fuel cycle (Davidson, 2006). For SNF however, the amount of repository space required is driven by the amount of decay heat that will be imparted to the surrounding geology over time. After the decay of fission products, decay heat is dominated by TRU elements, especially ^{238}Pu and ^{241}Am generated by ^{241}Pu decay, and the long-term heat load leads to an even lower drift loading factor for waste from the open fuel cycle. Early reprocessing of spent fuel and separation of plutonium can largely reduce heat generation from HLW so that decay heat is less a constraining factor for reprocessing waste. Taking volume and heat constraints into account, a given DGR disposal volume may take up to four times more reprocessing waste than that of the equivalent SNF (Davidson, 2006). In the partially closed fuel cycle considerations need to be given to the management and disposal of spent MOX fuel, which counteracts some of the advantages described above.

4.6.2. LILW

In the open fuel cycle basically all radioactivity produced during power generation in the reactor is confined in the spent fuel element that will be sent, after appropriate cooling time, to the repository.

While through recycling the amount of HLW to be disposed of is reduced in comparison to the open fuel cycle, significantly greater quantities of LILW-LL are generated during reprocessing. These waste streams consist of the structural parts of the fuel element (spacers and end-pieces) which are removed from the elements before dissolving the fuel and the cladding hulls that are not dissolved during reprocessing. In addition, there is technological waste: fines from the dissolution of spent nuclear fuel, filters of various kinds as well as ion exchange resins, spent reprocessing chemicals, evaporator concentrates, sludge that may contain both transuranic elements and long-

4. The drift loading factor describes the amount of waste that can be disposed in a given repository drift volume.

lived fission products, and scrap and trash from handling of fissile materials (IAEA, 2009a). The volume of these LILW-LL waste streams is larger than that of the vitrified HLW and poses considerable challenges for conditioning, handling and storage. For instance, the United Kingdom encapsulates uncompacted ILW in cement typically in highly engineered 500 litre stainless steel drums or in higher capacity steel or concrete boxes, whereas France, until the late 1990s, conditioned the structural parts by grouting them in cement and sludges and effluents in a bitumen matrix. In the Russian Federation, uncompacted ILW is stored in canisters.

New waste management techniques have been developed to mitigate some of the issues linked to the conditioning, storage, transportation and disposal of LILW-LL from reprocessing. In the French reprocessing plant in La Hague, the structural parts of fuel elements are now highly compacted and packaged in universal canisters of the similar type as those used for vitrified HLW. Each canister is filled with 5 to 7 discs according to their thickness, in order to produce less than 1.5 universal canisters per tonne of reprocessed spent fuel, a four-fold reduction compared to earlier methods (IAEA, 2005a). Certain parts of the technological waste like sludge and effluents are vitrified in a similar fashion to HLW, also using the universal canister type. The advantages of adopting a single type of canister for the different parts of the LILW-LL waste streams are obvious: these can be handled with the same tools; transported, stored and stacked with the same means and disposed of together in the same structure (Chotin, 2000).

4.6.3. LLW

In terms of the types of waste suitable for near-surface disposal, the present reprocessing fuel cycle produces a volume reduction of 20%, compared to the open fuel cycle. This reduction is driven by the lower need for fresh uranium, which in turn means less uranium mill tailings as well as smaller volumes of depleted uranium and LLW generated by processes at the front end of the fuel cycle (see also Section 4.5). This effect is even larger for the fully closed fuel cycle. The reduction in the volumes of waste from uranium mining dwarfs the additional volume of LLW produced by reprocessing and recycled fuel fabrication facilities. Low-level waste produced by reactors and all fuel cycle facilities amounts to less than 1% of the volume of tailings. Depleted uranium from the enrichment of natural and reprocessed uranium, which may not be suitable for shallow disposal in large quantities, also amounts to less than 1% of the tailings volume (BRC, 2012a).

4.7. Transport

Although transport of SNF/HLW has an excellent safety record, it constitutes a matter of concern to the communities along the transportation route(s) as well as the general public, often becoming the centre of public dissent.

There are three modes of transportation for SNF/HLW: road, rail, and water, which may be combined and which, individually, present different sensitivities to the host and route communities. Transport of radioactive material is highly regulated, with stringent safety standards set internationally by the IAEA or based on modal regulations as, for instance, the codes of the International Maritime Organisation. The fundamental principle for transport safety is based on the use of transport containers, which, for SNF and HLW are very robust casks providing mechanical integrity and the required gamma and neutron shielding, even under extreme accident conditions. Many of these casks can also be used as storage casks. Each cask can take one fourth of the annual discharge of a typical 1 000 MW reactor and may weigh more than 100 tonnes, with a cost of more than USD 1.5 million for the larger ones.

There is extensive experience with the shipping of spent fuel, using rail, road and sea transport. Over 80 000 tHM have been shipped in some 7 000 shipments, most of them to the reprocessing facilities in France (40 000 tHM) and the United Kingdom (30 000 tHM) (WNA, 2011); some 300 sea voyages have been made carrying spent fuel or HLW with specially designed ships from Japan to Europe (160 shipments) or from Swedish plants to the Swedish central storage facility.

Nuclear material transport is generally conducted by specialised companies and has proven to be very safe. Although over the years there have been transport accidents, a container with highly radioactive material has never been breached or has never leaked (WNA, 2011). Nonetheless, transport of HLW, SNF, plutonium, fresh MOX fuel and some forms of ILW that need special consideration for technical, safety and security reasons, has been a particularly sensitive issue with respect to public acceptance. Moreover, as transport represents the most exposed part of the entire fuel cycle, it can become the focus of social protests which, in fact, voice public concerns not necessarily related specifically to transport issues as such, but more generally linked to the perception and acceptance of nuclear energy and the fuel cycle as a whole (including safety concerns, e.g. fears associated with accidents, terrorist attacks and hijacks, etc.).

The difficult planning of transportation routes for defence-related transuranium waste from many points in the United States to the WIPP disposal site in New Mexico, the discussion on the transport routes in Nevada to the planned Yucca Mountain geological repository, and the violent civil conflict in Germany about rail transportation of HLW to a central storage facility (necessitating about 20 000 police to secure the transport) bear witness of the potential for conflict attached to transportation issues. The decision taken in Germany to limit transportation by refraining from the use of a central facility to store spent fuel and instead building and licensing 12 local facilities at reactor sites gives some indication of the economic value of public acceptance of transportation.

In the open fuel cycle, the spent nuclear fuel is regarded in its entirety as waste. Its permanent disposal, in one centralised DGR, as typically envisaged, entails a transportation programme from individual nuclear power plants or interim storage sites (local at the reactors or centralised) that, depending on the expanse of the country territory and the size of its nuclear programme, can be very extensive.

Some disposal concepts also foresee the conditioning or encapsulation of fuel rods before their disposal and the use of special disposal casks. The encapsulation and repacking is done in special facilities, which can entail a corresponding transportation leg. In some cases, close co-location of part or all of storage, conditioning and repository facilities is considered, which reduces the number of long-range transport legs, as is envisaged in Sweden (location of the encapsulation plant close to the centralised storage) or in the German Gorleben project (which, albeit now rather uncertain, foresees the co-location of storage and conditioning, both close to the planned repository).

As no country yet operates a repository for SNF direct disposal and only some of the countries that have adopted the open fuel cycle use centralised interim storage facilities, only about 5% of all used fuel shipped away from NPPs worldwide since 1971 can be associated with the open fuel cycle (WNA, 2011).

A fuel cycle based on reprocessing and reuse of the separated fissile material requires supplementary facilities and therefore, potentially, additional transport legs. As national commercial reprocessing facilities are built to deal with the entire spent fuel of a country – or at least a large portion of it – they tend to have considerable integrated buffer storage capacities. In these cases, in practice, the need for centralised storage capacity separately located is reduced and the reprocessing facility acts like the (only) hub for the transportation of spent fuel from NPPs. Also for countries using existing reprocessing facilities abroad, the need for their own longer-term interim spent fuel storage is alleviated (NEA, 2011a), but, conversely, international long-range transport legs would be generally needed, adding special measures and different requirements. Likewise, the

HLW produced – less in volume than the related SNF – is stored intermediately at the reprocessing plant, so that in fuel cycles with reprocessing the number of transportation legs is comparable to those required in an open fuel cycle with a centralised intermediate storage facility. The actual number of shipments to a final repository will be less, due to the lower volume of the HLW in comparison to the volume of the related SNF that has been reprocessed.

However, besides HLW, the reprocessing plant generates different streams of nuclear material that need different transportation requirements: the ILW from the structural parts of the fuel elements reprocessed that need to be transported to storage facilities and/or a repository, the separated Pu and U that will be sent to the fuel fabrication plant and the fresh MOX fuel that will be sent to reactors. The ILW (compacted structure elements) has about the same volume as the HLW, however the entire volume for transport of the packed waste from reprocessing is still about half of that from the corresponding SNF[5] (BFS, 2012).

Depending on the mode of transport, the sites chosen for the back-end facilities and the existing transportation infrastructure, considerable investment may be needed to implement a reliable transportation system. This might entail strengthening and upgrading existing roads, railways or bridges, or constructing new ones, including, for instance, to bypass densely populated areas or to develop special terminals for the change of mode of transportation. In case of sea transportation, which seems to have less potential for social conflict, the corresponding infrastructure of terminals, harbour and special ships need to be put in place. Long-range sea transport in international waters may also need special security measures to protect against possible terrorist attacks.

Thus, although transport issues should not hinder the implementation of waste management facilities at large, they could have important implications particularly associated to security and acceptance aspects, related risk of disturbances or time delays due to difficulties in reaching agreement with affected communities, or actual protest actions during the transport. This might affect the choice of the preferred storage strategy (as it did, for instance, in the case of Germany, discussed above) and may have an impact on costs, adding to the need to invest in special infrastructure, dedicated transportation casks and transportation vehicles.

To minimise these costs and to increase the reliability of the transportation system, careful consideration should be given to the siting of back-end facilities. Co-location of facilities may present possible advantages; for instance by co-locating reprocessing and DGR facilities, the number of transports may be reduced. However, such advantages must be cautiously weighed against other important factors (e.g. related to the safety of the site, as well as technical, environmental, sociopolitical and economical aspects) that matter in the siting of individual nuclear facilities.

4.8. Development of fast reactors and advanced fuel cycles

A key factor affecting a wider and sustained adoption of SNF recycling is the development of fast reactors and advanced nuclear fuel cycles. With fast reactors, the energy recovered from the original uranium can be 50-100 times higher than for the once through use of uranium fuel in LWRs. This will require advanced fuel cycles with multiple reprocessing and recycling in fast reactors that would also largely reduce the amount of very long-lived high-level waste, since Pu and minor actinides are partly burned.

5. This can be estimated from data given in BFS (2012), assuming 24 Cogema standard containers or 10 tHM (SNF) per Castor transportation cask.

Fast reactors have been under development since the 1950s and, in fact, the first reactor producing electricity in 1954 was a fast reactor. Since then, a considerable number of experimental and prototype fast reactors have been built and operated. For different reasons, however, fast reactors have not been developed at a commercial scale. Prototype reactors have been delivered at high costs, experienced technical problems, e.g. with maintenance of components in the sodium coolant, and – with the exception of the BN-600 – achieved only low capacity factors. Importantly, other external factors discouraged the commercial deployment of FRs: notably the low uranium prices and the political resistance founded in proliferation concerns, as well as the high capacity factors and good experience accrued with the existing fleet of thermal reactors.

For these reasons the total operating experience of fast power reactors has remained quite limited: a few 100 reactor years, compared to over 14 500 cumulative reactor years for thermal reactors. Only one fast power reactor has been in operation over a long time (>30 years) with a good capacity factor: BN-600 in the Russian Federation, where one more FR, BN-800, is under construction.

As detailed in the list below, over the last decade some countries have been reactivating their fast neutron reactor programmes, in the context of a long-term perspective of energy sustainability and security of energy supply, in conjunction with the reconsideration of current nuclear fuel cycles and the development of advanced fuel cycles:

- **People's Republic of China** has started the construction of a sodium-cooled FR based on Russian technology.
- **France** plans to build a prototype sodium-cooled fast reactor with a targeted start-up date of 2025. In parallel a gas-cooled fast reactor is being developed as an option.
- **India** is building a 500 MWe prototype sodium-cooled fast reactor, with planned start of operation in 2013, to be followed by another three reactors at the same site.
- **Japan** was operating the Monju fast reactor and was looking at a prototype power reactor to start tests in 2025. The situation of these projects is, however, unclear after the Fukushima Daiichi accident.
- **Russian Federation** is actively developing its fast reactor programme with the construction of BN-800 to start up in the near future and with plans for a BN-1200 by around 2020. Both are sodium-cooled FRs. Also a lead/bismuth-cooled fast reactor is being considered.
- **United States** is studying an advanced burner reactor able to burn plutonium and minor actinides separated from commercial LWR fuel (although this programme is not very active now).

Other countries and the European Union are also involved in some work on fast reactors. Much of the co-operation on research is conducted through the Generation IV International Forum (GIF, 2011) and through co-operation in Europe.

However, to evaluate the potential of fast reactor technology to strongly influence back-end strategy choices, it is important to consider the time horizon necessary for their large scale commercial deployment. The transition to systems based on fast neutron reactors and closed fuel cycles is a challenging endeavour (NEA, 2009), requiring careful long-term planning to evaluate the dynamic evolution of mass flows of fissile materials and their appropriate management at all steps of the fuel cycle, as well as to ensure continuing security of supply. Infrastructure adaptation is another key challenge and building industrial capabilities adapted to the transition period might be difficult at a national level. The deployment and penetration of fast reactor systems and associated FC services still present technological challenges. Each of the six conceptual nuclear energy systems selected for collaborative R&D in the GIF programme (sodium-cooled fast reactor [SFR]; very high temperature reactor [VHTR]; supercritical water-cooled reactor [SCWR]; gas-cooled fast reactor [GFR]; lead-cooled fast reactor [LFR]; and molten salt reactor [MSR]) has reached a different stage of development, depending on the R&D efforts made in the past and the level of commitment received from participating countries. The most mature Generation IV concepts are the SFR and VHTR, which are based on proven technology. These are the leading candidates for large-scale demonstration projects, the first of which could be in operation in the 2020s. Other reactor concepts may require smaller-scale prototypes before full-scale demonstration. As well as the development of reactors, R&D on advanced fuel cycles is an important aspect of the GIF programme. Notably, the development of advanced fuels with a system-wide integrated view taking into account recycle (separations) and waste forms is crucial for the implementation of advanced fuel cycles (NEA, 2011a). Different areas of fuel development are identified in the NEA study *Nuclear Fuel Cycle Transition Scenario Studies – Status Report*, published in 2009 (NEA, 2009).

The first commercial Generation IV systems are not expected to be available before the 2030s, with their full introduction unlikely before the 2040s. Hence, Generation IV reactors are not expected to be a major part of installed nuclear capacity until well after 2050 (NEA, 2012b and NEA, 2011a). This means that fast reactors will not be available for a bulk replacement of the existing fleet of reactors, anticipated around 2020-30. Instead they may be more gradually introduced to provide additional power after 2050. As the next NPP fleet replacement will only occur around 2080-90, the introduction of fast reactors at a large scale is expected to start sometime in the second half of this century.

Earlier deployment of FRs might be driven by political decisions in some countries, but this would need to include financial incentives for the transition to such new technologies. Such incentives appear necessary as ultimately it would be the utilities which have to implement and operate the new facilities, and utilities show some reluctance and inertia in investing in technologies that are not already well proven. As discussed in Section 2.3.2, in some cases, in order to achieve greater flexibility for the implementation of future technological developments (notably FR systems), planning of longer-term interim storage of SNF is taken as an effective interim stance. However, as already stated, prolonged interim storage cannot replace a definitive solution.

It should be noted that at the time when fast reactors could be commercially available there will be already a large surplus of fissile material in spent fuel. LWR plutonium is important for starting a fast reactor, but in the longer term FRs will generate their own plutonium from depleted uranium, which will be the main fuel resource. Reprocessing of the bulk of LWR fuel would thus not be chosen from an energy conservation perspective.

The costs for a fast reactor fuel cycle are highly uncertain. This is valid both for the investment costs in reactors, which are expected to be larger than for an LWR, and in fuel cycle facilities (reprocessing plants and fuel fabrication facilities), as well as for the costs of operation, which will strongly depend on the capacity factor. The comparably smaller volumes of waste with less long-term heat production and radiotoxicity to dispose of would probably lower the operational costs of the geological repository, or reduce the number of repositories needed for an expanded use of nuclear power.

4.9. Retrievability of waste

Disposal of radioactive waste in a deep geological repository aims to provide a permanent, long-term containment of the waste from the biosphere that does not need further human interaction. The concept of disposal – versus that of storage – implies that there is no intention to handle the waste again. However, for more than a decade the possibility of retrieving nuclear waste once already emplaced in a geological repository has been increasingly considered and, recently, addressed extensively (NEA, 2011; NEA, 2012).

The retrievability of nuclear waste is closely related to the concepts of "stepwise decision making" or "adaptive staging" in the implementation of DGRs, as discussed in Section 2.3.2. Provisions to facilitate retrievability of waste aim to extend the flexibility to change decisions or to reverse actions also beyond the time of waste emplacement. In this context, the option of retrievability is often associated to that of reversibility and the whole integrated scheme is referred to as "reversibility and retrievability", with the two distinct terms meaning:

- reversibility – the ability to reverse one or a series of steps in the repository development at any stage of the programme;
- retrievability – the ability to retrieve emplaced waste (including entire waste packages).

The reasons for introducing retrievabilty concepts into the design and operational procedures of a geological repository are very disparate, ranging from ethical considerations, e.g. preserving the "ability of future generations to meet their needs and aspirations"; technical factors, e.g. improving the capability to handle technical safety concerns that may be recognised only after waste emplacement, or using alternative waste management techniques that may be developed in the future; to strategic arguments, for instance the consideration that nuclear material treated as waste today might be seen as a resource in the future (NEA, 2011). This last point is closely tied to the open fuel cycle and is probably a tacit consideration in several cases where direct disposal of spent nuclear fuel is adopted; although, strictly speaking, this position would probably call for a formal policy towards long-term storage rather than disposal.

Conversely, there are also concerns that measures introduced to facilitate retrievability may adversely affect the operational and long-term safety of the repository. Arguments raised include the possible increase in radiological exposure of workers, risks of compromising some inherent safety and security features of geological disposal, challenges to seal the repository properly and the potentially reduced protection against irresponsible attempts to interfere with the waste (e.g. during times of political/social turmoil) (NEA, 2011).

In many countries with an advanced geological disposal programme, reversibility and retrievability is a fundamental feature. However, only some countries have laid down formal statutory requirements for a retrievable design of the repository in their legislation (i.e. Finland, France, Germany, Hungary, the Netherlands, Switzerland and the United States). The choice for reversibility and retrievability seems to be largely independent from the fuel cycle policy, as nations with legal requirements for retrievability are both reprocessing (France) and non-reprocessing countries. The legal provisions may define the timeframes over which retrievability needs to be assured or tie reversibility and retrievability to specific stages of the repository lifecycle (e.g. until repository closure as is the case for Switzerland), or specify more detailed required features too.

The option to retrieve waste from a geological repository has technological implications in terms of the design of the disposal system and the associated repository infrastructure. The effort involved in any retrieval operations and thus the associated costs will depend on specific design characteristics (containers, emplacement cells with or without buffer materials, repository access ramps or shafts, (IAEA, 2009; NEA, 2011). Certain common repository design features (e.g. the use of long-lived waste containers) are inherently beneficial in terms of the ability to retrieve waste. However, certain additional provisions are required to facilitate waste retrieval. Factors of particular interest for the development of retrieval strategies in the pre-operational phase may include the (self-sealing) properties of the host rock and specific aspects of repository design such as the degree of backfilling and sealing of repository openings and connection of the repository to the surface. There are also other, managerial factors to be considered, such as cost, timescales, risk reduction, hazard identification and mitigation, the complexity of the aged waste and waste package, the accuracy of inventory knowledge, the scale of the task (volumes to retrieve) and the required downstream processes (repackaging, conditioning, treatment, final waste disposition) (NEA, 2011). The timing and in particular the delay between waste emplacement and retrieval may even affect the feasibility and practicability of retrieval, as well as its costs. In particular, if an extended period of repository operations is required beyond the timescales needed for waste emplacement the implementation of a retrievability option could substantially increase the repository lifecycle cost.

At present there is no experience in determining the added costs of retrievability implementation; however, the following main cost categories can be identified (NEA, 2011):

- costs for design changes and upgrade of repository components, e.g. enhanced containers, special emplacement room design;
- costs for enhanced maintenance related to delaying the closure of emplacement areas or for making it not final;
- costs to prepare for actual retrieval operations, e.g. retrieval machinery.

Additional costs depend on the scope of retrievability set by regulations and may range from costs of demonstration to costs for additional facilities needed for retrieving the waste and storing it.

The costs of the actual retrieval operations, should these be pursued at some point in time, are likely to be comparable in magnitude with those of the construction of the associated repository areas and related emplacement operations.

The question of responsibility for costs is also important. As far as retrievability is stipulated in the national law and/or subsequent regulatory requirements, it becomes a requested feature for the repository and all associated costs are to be dealt with under the provisions in place for waste management as such. In cases where the retrievability option is deliberately left open in national law and private operators are in charge of implementing disposal, it is their decision to include retrievability or not, and consequently they will have to bear associated costs (Canada, Sweden). Public implementing institutions may need a legal basis to introduce retrievability into their concepts, as there is an established view that retrievability is not needed for the safe operation of a repository, including its long-term safety. On the other hand, costs for the actual retrieval of waste and its subsequent management (including the management of any secondary waste), must be the responsibility of those opting to retrieve, except when the decision is taken on the basis of safety concerns.

To summarise, it can be stated that the implementation of a geological disposal may have significant additional costs associated with the option of waste retrieval. In principle, as the lifecycle of the repository progresses towards more advanced stages, and particularly with waste emplacement (e.g. in disposal cell, in sealed cell, in sealed disposal zone, closed repository), the costs to maintain retrievability as an operational feature increase and the actual retrieval becomes more complicated (NEA, 2012a). There is no indication that the additional costs of a retrievability option are substantially different for geological disposal of spent fuel or of HLW from reprocessing, given the same volume of waste/spent fuel. The cost of managing retrieved waste might be substantial. However, for open fuel cycles retrievability would broaden future policy options for the nuclear fuel cycle.

4.10. Legal and regulatory aspects

Legal frameworks in the nuclear field are sets of special, legally binding rules created to regulate the conduct of entities engaged in nuclear activities. Several fundamental concepts or principles are reflected in these legal frameworks: concepts such as safety, security, responsibility, permission, continuous control, compensation, sustainable development, compliance, independence, transparency and international co-operation. At the national level, a legal framework is normally founded on legislation (including regulations), while at the international level it is comprised of one or more legally binding international instruments such as treaties, conventions and agreements.

A recent comparison of national legal frameworks in a number of countries with nuclear power and partly also reprocessing (Streffer, *et al.*, 2011) shows that in spite of common fundamental safety concepts the structure for legal provisions in particular for the back end of the fuel cycle can be quite different. At the level of statutory regulation, radioactive waste disposal is covered either in special statutes, or in general nuclear energy laws. In the latter case, specialisation of regulation occurs at a lower level of legislation or/and in administrative regulatory provisions. Legal provisions vary substantially across countries, showing different degrees of detail (e.g. high in Finland, France, Sweden, Switzerland and the United States, and lower in other countries, as noted in Streffer, *et al.* [2011]), and being more or less prescriptive. For instance, the nuclear legislation/regulation regime for waste disposal in the United Kingdom is based on goal setting, in contrast to those in the United States and France which are prescriptive.

The legal framework of a country may also constrain policy decisions regarding the basic strategic option for the fuel cycle, i.e. open fuel cycle with direct disposal or reprocessing. In some countries one or the other option is fixed in the relevant statutes, e.g. direct disposal in Finland, Germany and the United States, or reprocessing in France and Japan. On the other hand, policy decisions on fuel cycle options can develop *de facto* normative power comparable to statutory provisions, as demonstrated by the rejection of reprocessing in Sweden, which is not requested by statute in this country. Laws can also be changed should the boundary conditions change.

Whether at national or international level, legal frameworks must be sufficiently flexible to adapt to possible future developments and changes in the nuclear power sector, including the introduction of facilities for reprocessing or more advanced fuel cycles. Such developments are not likely to lead to the creation of new concepts, but they will almost certainly need additional efforts to adapt the existing ones to new types of facilities. As regulations are not defined for new technologies, work will be needed to develop these and regulatory bodies may be faced with a dearth of competencies.

4.11. Safety aspects

In general terms, the safety of a nuclear installation can be understood as the ability of its systems and personnel to, first, prevent accidents from occurring, and, second, should an accident occur, to mitigate its consequences. The safety of a nuclear facility relies on engineered protections built into its design and based, in particular, on the concept of defence-in-depth, which provides multiple independent layers of protection against the release of radioactive substances. Crucially, nuclear safety must also be based on the organisation, training, procedures and attitudes of the operator. Although the design and operating features of nuclear plants and processes are developed to minimise, as far as possible, the impact that operator errors (of commission or omission) may have, people remain the ultimate guarantors of safety. Hence the establishment and maintenance of robust safety culture remains a key pillar of highest priority in nuclear safety. Nuclear safety also relies on the verification and inspection activities carried out by an independent regulatory body, with the powers to suspend the facility operations if safety requirements are not fully met (NEA, 2012b). This institutional safety framework is based on the licensing experience of about 450 commercial NPPs and over 14 500 cumulative reactor years of operation and it ensures that only plants and operations that are considered safe are licensed. This basic system, well developed for NPP safety, is also applied to all nuclear facilities including those of the back end of the fuel cycle, and notably reprocessing, waste management and disposal.

Nevertheless each of the FC options has different radiological risk profiles. The nature and conditions of plants and processes adopted in nuclear fuel cycle facilities (front and back end) are very different from those involved in nuclear reactors and thus present safety hazards of different nature and degree. Radioactive materials to be handled are present in many parts of FC facilities but, generally, in a less concentrated form than in nuclear reactors. Furthermore, nuclear fuel cycle facilities, including reprocessing plants, are operated at relatively low temperatures and pressures and in subcritical conditions, thus holding a more contained potential energy content, which limits the possibility, in abnormal conditions, of rapid excursions towards dangerous situations (NEA, 2005). On the other hand, in general terms, the introduction of extra steps and processes in a system and the handling of radioactive liquids and powders have the potential of posing added hazards. Thus, in comparison to an open fuel cycle, reprocessing presents specific safety challenges, due to internal and external hazards. Equally, for some of the advanced systems, different safety issues have to be addressed, which are not common to those related to the dominant LWR technology; however, the objective remains that the same safety standards be maintained or exceeded (NEA, 2011a).

Of particular concern for reprocessing plants are criticality and chemical hazards, as well as fires and explosions. The latter receive the greatest attention, due to the use of industrial quantities of flammable solvents and chemical reagents in the PUREX process (NEA, 2005). In addition, many sections of the fuel cycle involve energy releasing or absorbing processes; high heat ratings result for instance from fission product heating. Failure of equipment for the cooling or the control of hydrogen producing radiolysis may lead to fire and explosion. Fuel cycle facilities (including various in the front end) handle and store large volumes of toxic products and corrosive (generally non-radioactive) materials. For example, the production of uranium hexafluoride (UF_6) involves the use of significant quantities of chemically toxic hydrogen fluoride which poses a significant hazard to workers. While the fuel cycle industry has maintained excellent safety records regarding these hazards, accidents have occurred in research facilities (e.g. a bitumen fire at the PNC [Power Reactor and Nuclear Fuel Development Corp.] facility in March 1997, or the criticality event at JCO facility at Tokai Mura in September 1999) demonstrating their potential safety impact.

Although the few existing commercial reprocessing facilities have been operating for several decades (e.g. La Hague started in 1967), the base for operational feedback is not as extensive as for NPPs that, by and large, use standardised technologies. Nonetheless, over time, improvements in aqueous reprocessing technologies have led to a sustained optimisation of treatment processes and the reduction of the level of discharges to the environment (NEA, 2011a). The continuous reduction in discharges to atmosphere or waters, as well as of exposure to workers, represents an important evolution in reprocessing safety. The increased reliability of equipment (which reduces maintenance and thus doses), along with the implementation of the ALARA principle has contributed to lower worker exposures.

With regard to the safety of deep geological repositories, which inevitably represent the endpoint of any fuel cycle, the distinctive functions and conditions characterising these facilities require addressing certain hazards and thus implementing safety features which are quite specific. Given the exceptional longevity required of such systems, passive "multi-barrier" safety is central to ensuring their long-term robustness. Some further details on DGR safety are provided in Chapter 2.

4.12. Summary

This chapter analyses a number of qualitative factors that, in addition to cost considerations, may have an important impact on any decision making regarding back-end options for the nuclear fuel cycle. These cover:[6]

- political issues, like security of supply and non-proliferation;
- issues of administrative, governmental infrastructural and social nature, like regulation, safety, public attitudes and transport; along with
- more technical aspects, like environmental protection, retrievability, safety, waste production and future technological developments.

All such factors come into play in the evaluation and comparison of different back-end options. However, their relative importance is intricately linked to specific national contexts and may even shift over time. Therefore, different factors may outweigh others in different countries and in different temporal contexts. For instance, in countries lacking internal energy resources like France, the Republic of Korea or Japan, security of supply is a dominant priority. Technological factors that, a priori, may have favoured one fuel cycle over another could become less important.

Security of supply and non-proliferation concerns are qualitative factors with a strong political driver. As in the majority of cases, uranium requirements are satisfied mainly by imports, geopolitical risks linked to difficulties in the international uranium market, or politically motivated interruption of supply cannot be excluded. However these concerns are modest, as U resources are globally well-distributed and relatively abundant, with broad and long lasting availability (compared to fossil fuels). Further, reactor operating costs are not greatly affected by price volatility and are resilient to changes in carbon policies. Nuclear in general improves energy supply security. With reduced demand for fresh natural uranium, reprocessing options enhance even further energy supply security, by also introducing greater technical and local diversity of facilities and services, thus broadening the resource base and favouring the emergence of competitive markets.

With its strong political support, proliferation resistance can have a profound influence on civil FC policies, determining the adoption or rejection of back-end strategies or deeply shaping them. This was the case in the United States, which, due to considerations of proliferation resistance, abandoned civil reprocessing in the 1980s; or in the Republic of Korea which agreed in the past, for non-proliferation reasons, to abstain from the development of sensitive technologies including reprocessing. In this respect, the open fuel cycle is generally perceived as being more proliferation resistant, as it keeps Pu produced during reactor operation within the spent fuel and thus in a form difficult to divert. In contrast, the recovery of fissile material and the separation of pure streams of uranium and plutonium pursued in the basic reprocessing cycles have historically been regarded as key vulnerabilities for non-proliferation. While technical and procedural measures are in place that try to keep the amount of separated fissile material in reprocessing options as low as possible (including the prompt recycling of separated plutonium), this remains a political concern. The future introduction of advanced fuel cycles and reprocessing methods that move towards technologies with no extraction of pure plutonium streams could significantly contribute in further alleviating such proliferation concerns. Multilateral approaches limiting the deployment of sensitive national facilities have also been advocated to enhance proliferation resistance.

Like many large industrial or infrastructure projects, back-end facilities are subject to societal concerns and in some cases can even provoke public protests. Failing to obtain public support for any FC strategy can severely hamper the development of facilities and

6. This is not a rigid categorisation, and some of the identified factors may belong to more than one sphere of influence.

programmes or lead to considerable delays and escalating costs. Regardless of the type of high-active waste to be disposed of (whether HLW from reprocessing or SNF from a once-through fuel cycle), to which public attitudes seem largely indifferent, unresolved societal issues have been one of the main reasons that many DGR programmes have not proceeded as planned. Social challenges for siting reprocessing plants have also seen major opposition, as it was the case in Germany where a project to construct a reprocessing facility was stopped essentially due to civil protest. However, in general, public attitude towards reprocessing plants seems more akin to that associated with nuclear power plants or front-end facilities. One reason for this may be that, contrary to DGRs, these facilities offer economic incentives to local communities, which can help to trade off disadvantages, perceived or real, of hosting such facilities.

Transport of SNF/HLW can be a matter of concern to local communities and the general public. Transport represents the most exposed part of the entire fuel cycle, and as such it can become the focus of protests, voicing broader concerns linked to the general perception and acceptance of nuclear energy. Considerable investment may be needed to implement a reliable transport system, depending on the country size and topography, the geographical spread of its NPP fleet, the sites chosen for back-end facilities, the mode of transport and its existing infrastructure. Although issues related to transport are not expected to significantly hinder the implementation of back-end solutions at large, risks of disturbance associated with security, public acceptance and protest actions may lead to time delays and increased costs, and might even affect certain strategy choices. Germany, for instance, forewent the use of an existing SNF central facility and opted instead to build 12 local facilities at reactor sites to limit transportation. Co-location of facilities may present possible advantages which should nevertheless be cautiously weighed against other important factors (e.g. the safety of the site, as well as technical, environmental, sociopolitical and economical aspects). The lesser amount of waste generated in reprocessing fuel cycles may also favour transportation. However, in reprocessing fuel cycles the transport legs for separated U and Pu and for fresh MOX fuel – replacing transport legs for equivalent masses of natural U and UOX, respectively – introduce additional transport requirements (e.g. concerning shielding and robustness of the transport containers). Ultimately, the degree of influence of transportation over any fuel cycle is highly specific to a given situation and country and cannot be assessed in a generic way.

Safety and environmental impacts are of principal concern for all fuel cycles. For those incorporating reprocessing, however, supplementary facilities and handling of radioactive material add to what is otherwise part of the open fuel cycle, with the potential to increase safety, environmental and regulatory burdens. Although HLW from reprocessing undergoes reliable (and increasingly improved) conditioning (e.g. vitrification) for long-term final disposal, concerns about the radiological and environmental impact of the operation of reprocessing plants have figured prominently in public opinion and policy making. Nowadays though, the large body of operational experience, the improved processes and technologies have drastically reduced effluents from modern reprocessing plants, their radiological impact on workers, and thus the resulting collective doses. This, together with the increased reliability of equipment (leading to lower maintenance needs and reduced doses) and the implementation of the ALARA principle, represents an important evolution in reprocessing safety. The added radiological impact of the reprocessing option may be counterbalanced, for instance, by decreasing the needs in natural uranium, and thus the generation of tailings, for the same amount of energy produced, or by reducing the volume and long-term heat production and radiotoxicity of the ultimate waste disposed in the DGR.

Safety, security and environmental aspects (together with other principles) are embodied in regulation at the international and national levels. These latter however, in spite of common fundamental principles, can be quite different across countries in terms of structure and detail of legal provisions, in particular for the back end of the fuel cycle.

National legislation sometime excludes certain options, and, conversely, policy decisions on fuel cycle options can develop *de facto* normative power comparable to statutory provisions. The development of any back-end strategy entails the introduction of new facilities and technologies (whether for reprocessing, the deployment of more advanced fuel cycles or DGRs), and legal and regulatory frameworks must be sufficiently flexible to adapt to such changes. Since for some new technologies regulations are not defined, additional effort and competencies will be needed for their development.

Different types of radioactive waste are generated at each step of FCs, but their relative volumes and timelines can differ substantially depending on the cycle. One of the principal advantages of reprocessing is the reduction in volume and long-term heat production and radiotoxicity of the waste that needs disposal in deep geological repositories. Early reprocessing of spent fuel and separation of plutonium can also largely reduce heat generation from the waste – an important criterion for the repository volume needed for disposal. Taking volume and heat constraints into account a given disposal volume may take several times more HLW from reprocessing than of the equivalent SNF amount. The reduction of volumes and DGR footprint can be a driver in countries like the Republic of Korea where space is a scarce asset. In order for the current Korean nuclear programme and expansion plans to be sustainable, the volumes of waste must be drastically reduced; thus the Republic of Korea is more recently directing efforts towards the development of pyroprocessing and closure of the fuel cycle (NEA, 2011a), despite its previous stance with regard to reprocessing. However, if reprocessing greatly reduces the amount of HLW to be disposed of, on the other hand it generates significant quantities of LILW-LL. Modern techniques and processes like compaction and vitrification as well as the use of unified canisters ensure that the combined disposal volume needed for HLW and operational waste from reprocessing is still significantly less than that needed for disposal of unprocessed SNF.

Technical factors can affect the timing and costs for the deployment of back-end options and particularly more innovative ones. A prerequisite for a wider and more sustained adoption of advanced SNF recycling is the development of fast reactors and advanced nuclear fuel cycles. The technical problems experienced with prototype FRs, low public and political support in the past and uncertainty in economic parameters have limited the commercial deployment of FR systems and associated FCs. Although FRs are being built in the People's Republic of China, India and the Russian Federation, the timeframes required to address the remaining technological developments of Generation IV systems and related FC services will preclude their wide introduction for a bulk replacement of the existing fleet of reactors, anticipated around 2020-30. The deployment of Generation IV systems at a large commercial scale is expected to start only sometime in the second half of this century.

The implementation of specific technical characteristics in DGRs may be required to implement reversibility and retrievability, which may yield significant additional costs (these depend on the degree of retrievability to be achieved, the timeframe over which this should apply, as well as the geological environment). In many cases such features are simply built into the design of geological repositories; sometime they are part of the current national debate; and in certain instances they constitute a legal requirement. When this is the case legal provisions may detail specific retrievability needs and set out responsibilities for costs. If retrievability is stipulated in the national law and/or regulatory requirements, it becomes a requested attribute for the repository and all associated costs are to be dealt with under the provisions in place for waste management. Specific design features linked to reversibility and retrievability will be largely independent from the fuel cycle. Although one important reason for retrievability could be resource utilisation, it seems that the discussions about reversibility and retrievability are not strongly dependant on the choice of fuel cycle.

References

BFS (2012), Forecasts for future waste volumes (web page), update 13 December 2012, Bundesamt für Strahlenschutz, Salzgitter, Germany. www.bfs.de/en/endlager/abfaelle /prognose.html.

BRC (2012), *Blue Ribbon Commission on America's Nuclear Future*, Report to the Secretary of Energy, Washington, DC, the United States.

BRC (2012a), *Reactor and Fuel Cycle Technology Subcommittee,* Report to the full Commission, Blue Ribbon Commission on America's Nuclear Future, Washington, DC, the United States. Available at: http://cybercemetery.unt.edu/archive/brc/20120620220054/http:// brc.gov/sites/default/files/documents/updated_rfct_report_final.pdf.

Clavel, B. and P.Y. Hémidy (2008), "Stratégie et logique de surveillance de l'environnement autour des CNPE EDF", Conference on *Surveillance de la radioactivité de l'environnement,* Société française de radioprotection, on 23-24 September 2008, Paris, France. www.sfrp. asso.fr/spip.php?article59.

Chotin, F., *et al.* (2000), "The Atelier de Compactage des Coques (AAC) Facility: The R&D Programme", in Proceedings of the International Symposium on *Technologies for the Management of Radioactive Waste from Nuclear Power Plants and Back-End Nuclear Fuel Cycle Activities*, Taejon, Republic of Korea, in 1999, IAEA-SM-357/30, International Atomic Energy Agency, Vienna, Austria.

Davidson, D., *et al.* (2006), "Benefits of an integrated fuel cycle on repository effective space", WM'06 Conference, on 27 February-2 March 2006, Tuczon, AZ, the United States.

DOE (2008), *Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement – Summary*, DOE/EIS-0396, Washington, DC, the United States.

Euratom (2011), *Euratom Supply Agency – Annual Report 2011*, European Union, Luxembourg. Available at: http://ec.europa.eu/euratom/ar/ar2011.pdf.

GIF (2011), *Generation IV International Forum – Annual Report 2011*, OECD/NEA, Paris, France. Available at www.gen-4.org/PDFs/GIF_2011_annual_report.pdf.

IAEA (1980), *International Nuclear Fuel Cycle Evaluation* – INFCE (1977–1980), Summary Volume (INFCE/PC/2/9), International Atomic Energy Agency, Vienna, Austria.

IAEA (1998), *Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards*, INFCIRC/540 (Corr.), International Atomic Energy Agency, Vienna, Austria.

IAEA (2005), *Multilateral Approaches to the Nuclear Fuel Cycle*, Expert Group report to the Director General of the International Atomic Energy Agency, Vienna, Austria.

IAEA (2005a), *Status and Trends in Spent Fuel Reprocessing*, IAEA TECDOC-1467, IAEA, Vienna, Austria. Available at www-pub.iaea.org/MTCD/publications/PDF/te_1467_web.pdf.

IAEA (2009), *Geological Disposal of Radioactive Waste: Technological Implications for Retrievability*, IAEA Nuclear Energy Series, No. NW-T-1.19, International Atomic Energy Agency, Vienna, Austria. Available at www-pub.iaea.org/MTCD/publications/PDF/ Pub1378_web.pdf.

IAEA (2009a*), IAEA Disposal Approaches for Long Lived Low and Intermediate Level Radioactive Waste*, IAEA Nuclear Energy Series No. NW-T-1.20, International Atomic Energy Agency, Vienna, Austria. Available at www-pub.iaea.org/MTCD/publications /PDF/Pub1407_web.pdf.

IAEA (2010), *Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste*, IAEA Nuclear Energy Series No. IANW-T-1.21, International Atomic Energy Agency, Vienna, Austria.

IAEA (2012), "The Safeguards System of the International Atomic Energy Agency", International Atomic Energy Agency, Vienna, Austria. (accessed 2012_12_24) www.iaea.org/safeguards/documents/safeg_system.pdf.

NEA (2000), "Radiological Impacts of Spent Nuclear Fuel Management Options A Comparative Study", OECD, Paris, France.

NEA (2005), *The Safety of the Nuclear Fuel Cycle – Third Edition*, OECD, Paris, France.

NEA (2006), *Advanced Nuclear Fuel Cycles and Radioactive Waste Management,* OECD, Paris, France.

NEA (2008), *Nuclear Energy Outlook*, OECD, Paris, France.

NEA (2009), *Strategic and Policy Issues Raised by the Transition from Thermal to Fast Nuclear Systems*, OECD, Paris, France.

NEA (2011), "Radioactive Waste Management Committee, Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel", Final Report of the NEA R&R Project (2007-2011), OECD Paris, France.

NEA (2011a), *Trends towards Sustainability in the Nuclear Fuel Cycle*, OECD, Paris, France.

NEA (2012), *Reversibility of Decisions and Retrievability of Radioactive Waste Considerations for National Geological Disposal Programmes*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2012/7085-reversibility.pdf.

NEA (2012a), *International Understanding of Reversibility of Decisions and Retrievability of Waste in Geologic Disposal*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/rr/documents/RR_Leaflet.pdf.

NEA (2012b), *Nuclear Energy Today*, OECD, Paris, France.

NEA/IAEA (2012), *Uranium 2011: Resources, Production and Demand*, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD, Paris, France.

Streffer, *et al.* (2011), *Radioactive Waste – Technical and Normative Aspects of its Disposal*, Springer, Heidelberg, Germany.

UNSCEAR (2008), *Sources and Effects of Ionizing Radiation,* United Nations Scientific Committee on the effect of Atomic Radiation, UNSCEAR 2008 – Report to the General Assembly with Scientific Annexes; United Nations, New York, the United States.

WNA (2011), Transport of Radioactive Materials (Web page – updated July 2011), World Nuclear Association, www.world-nuclear.org/info/inf20.html.

Chapter 5. Summary, conclusions and recommendations

5.1. Introduction

Radioactive waste is produced in different industries which use radioisotopes, including medicine, agriculture, research and education. The largest volumes and radioactivity are however produced by the nuclear power industry, in nuclear fuel cycle processes. Low-level and short-lived intermediate-level waste constitute the largest volumes of radioactive waste, while only a small part is high-level waste, consisting by and large of packaged SNF for direct disposal or fission product residues from reprocessing. LILW-SL is generated at all stages of the FC, and for the back-end LILW-LL derives almost exclusively from reprocessing. Technology for the treatment, storage and disposal of low-level and short-lived intermediate-level waste is well developed, and almost all countries with a major nuclear programme operate disposal facilities for such waste.[1] The largest amount of radioactivity is however attributable to the smaller volumes of SNF and HLW for which no civil nuclear disposal facilities have yet been fully implemented. In addition, given the very long time frames involved, the uncertainties in costs and the related need to set aside the necessary financial resources for funding such future costs, the management of SNF and HLW is one of the key challenges the nuclear industry faces, as well as a matter of concern and public debate in many countries.

While various studies on SNF management costs have been carried out at a national level, there is no recent comprehensive overview of the state of knowledge on the costs of managing the back end of the nuclear fuel cycle across NEA member countries. Estimates conducted by individual countries inevitably reflect current national policy concerns and practices, thus generating results that are not directly comparable with those of other countries.

To address this issue, the current study was therefore initiated on the economics of the back end of nuclear fuel cycle and an expert group was established in 2011. The focus of the study was the long-term management of SNF and HLW, with the key objectives listed below:

- To understand economic issues and methodologies for the management of SNF in NEA member countries, including the funding mechanisms in place or under consideration, how the funds are managed and the extent of any unfunded liabilities.
- To assess the available knowledge from different countries on the costs of the various options for the long-term management and final disposal of radioactive waste, and to the extent possible, to compare the cost estimates of different countries on a common basis.

1. In countries with a sizeable fleet of NPPs, considerable experience is available on waste and materials processing, conditioning, storage, transport and disposal on low and intermediate level waste. For the management of LLW, in many countries all the steps have been implemented on a commercial scale. However, in some cases there are still issues related to special types of radioactive waste (e.g. mixed waste and graphite) that require further consideration. Technological developments may still be achieved in the future, but they are not expected to strongly influence LLW waste management options.

- To evaluate, in particular, the impact of uncertainties, for example, variations in cost estimates for SNF interim storage, reprocessing, encapsulation or final disposal.

The work was essentially based on nationally supplied official data, related to the management of SNF and HLW and its costs, and collected through a country questionnaire.

It should also be noted that in some countries substantial volumes of radioactive waste (legacy waste) exist from earlier, primarily military, activities, which will require substantial funding for clean-up. Such costs are not included in this study as the information available proved to be scarce and not amenable to analysis.

The outcome of the study encompasses a review of different back-end options and current policies and practices, financial arrangements and qualitative considerations on cost estimates in NEA countries (in Chapter 2); a cost assessment (in Chapter 3), including a comparative appraisal of existing economic models, and the development and application of a simple model for high-level cost estimates of idealised back-end strategies and sensitivity calculations (for the evaluation of uncertainty impacts and cost drivers). An analysis of the influence of other key qualitative parameters in the selection of back-end strategies is also undertaken (in Chapter 4), since factors other than economics are an important part of the decision-making process.

This chapter provides a synopsis of the main findings derived in the individual parts of the study. Conclusions are framed in boxes and numbered recommendations are reported in bold.

5.2. Current status and progress of national policies and programmes

5.2.1. National policies

For the long-term management of SNF, two major options have been adopted by countries with nuclear programmes:

- The once-through fuel cycle option, where fuel is used once and is then regarded as waste to be disposed of. Interim storage is followed by encapsulation and subsequent geological disposal of the SNF.
- The partial recycling option, where spent fuel is reprocessed to recover unused uranium and plutonium for recycling in light water reactors in the form of REPUOX and MOX fuel, respectively. HLW resulting from reprocessing is disposed of.

In general, used MOX and REPUOX assemblies are stored with the perspective of reprocessing and recycling them in future fast reactors that are not yet commercially available. A number of countries with major nuclear programmes operate or have plans to develop reprocessing and fuel fabrication facilities. However, currently only France and the Russian Federation offer continued services to other countries. In the United Kingdom all current contracts for the reprocessing of spent fuel will be completed by 2018, and reprocessing facilities will be subsequently closed. Some 10% of reactors worldwide have been licensed to use MOX, with uranium recycling carried out by a few reactor operators on a limited scale. With the significant experience accrued to date, the PUREX reprocessing technology and the use of MOX can be regarded as mature technologies.

In reprocessing countries, partial recycling is generally seen as an important intermediate stage towards the transition to full recycling in fast reactors. Advanced systems and fuel cycle concepts for the longer-term future have been studied theoretically or on a pilot scale, principally with the dual objective of reducing the mass and radioactivity of waste destined for final disposal and optimising the use of natural resources. However, the deployment of fast neutron systems and associated advanced

FCs will still require significant efforts in development and adaptation, including in legal and regulatory frameworks, increased investment and the development of new infrastructures for advanced systems and processes. The first commercial Generation IV systems are not likely to be available before the 2030s, and they are not expected to become a major part of installed nuclear capacity until well after 2050.

In the partial recycling option a high-level fission product waste stream which also contains the minor actinides is generated from reprocessing and will need permanent disposal. Even advanced options aimed at closing the fuel cycle need to manage residual actinides (from losses) and fission products, since the process is not completely efficient. Thus, regardless of the fuel cycle strategy adopted, facilities for final disposal of either HLW or spent fuel are required. There is general agreement that emplacement in deep geological repositories offers the best solution to this need. Hence, progress towards implementation of DGRs remains a high priority for the future use of nuclear energy. Studies for disposal are being pursued by countries that have opted for an open fuel cycle, as well as most countries that have opted for partial recycling.

Both industrial fuel cycle options (direct disposal or partial recycling), as well as any prospective advanced option, will ultimately require an operational repository for final disposal. The major difference in the deep geological repository needed for the different options will be in relative size.

Owing to political and societal hurdles in some countries, challenges in the establishment of a national SNF strategy have been experienced and, in some instances, have caused significant shifts over time. For this reason, or sometimes as a result of a considered choice, a few countries have been holding off from developing firm or single strategies. These situations, together with the long timeframes often needed for the deployment of final repositories, have led to extended intermediate storage times. Other factors that can also influence continued long-term storage include the small volumes of waste accumulated in the country, difficulties with transport or site selection, or inadequate available funding. In most cases, interim storage facilities were initially designed to operate for periods of up to 50 years, but operational periods of 100 years or longer are now being envisaged. While long-lived solid radioactive waste and SNF have been safely and securely stored in member countries for several decades now, the much extended interim storage times raise questions in relation to long-term integrity and the safety of spent fuel elements.

Recommendation 1

While there may be reasons to extend the interim storage of SNF, these should not prevent governments from maintaining vigorous efforts towards the establishment of deep geological repositories, thereby addressing legitimate public expectations and fulfilling the “intergenerational equity” principle.

5.2.2. Progress in DGR implementation

No civilian DGR for SNF and HLW has yet been built in the world; however, relevant national legal and regulatory frameworks are in place with some examples of good progress seen in disposal programmes. The technology has been developed and is expected to be fully implemented by the mid-2020s, when three DGRs are planned to become operational. The most significant advances have occurred in countries with a long-term continuity in policy positions, as is the case in Finland, France and Sweden, where deep geological repositories are expected to start operations in the next decade. In other countries, longer time horizons have been envisaged, spanning from two to many decades.

Waste management organisations have been established in most NEA member countries. WMOs are generally separate non-commercial entities that can have various responsibilities, from the centralised collection of SNF/waste and the related processing capabilities to final disposal. They can be either state-owned organisations or organisations that are owned by waste producers. Their compound responsibilities require a set of attributes encompassing technical capability, accountability and, ideally, organisational stability and political independence. They also play a key role in negotiating with relevant stakeholders and seeking consent, primarily for the siting of a DGR.

Stakeholder engagement at the different stages of programme implementation is crucial to the success of DGR implementation, and stepwise approaches that foster greater flexibility and partnerships with potential host communities are increasingly favoured. In some countries this move has resulted in improved public acceptance.

> Advances have occurred in national programmes for HLW and SNF disposal. Conditions favouring progress include the maturity of the industry, the long-term continuity in policy positions and a high degree of emphasis on community partnerships in the implementation of strategies.

Recommendation 2

Public involvement in the establishment and implementation of the SNF management strategy is considered vital, and mechanisms to improve stakeholder participation and transparency should be a high priority.

5.2.3. Funding and costing

Most countries perform assessments of the costs for SNF/HLW management, encompassing the different stages of the back end (e.g. interim storage, encapsulation and transport as detailed in Section 2.1 and Table 2.4). Factors influencing such costs are manifold and often country specific (e.g. different physical and technical conditions, individual national regulations, economic conditions, different itemisation, boundary conditions and scope of cost estimates). Thus, cost estimates obtained in different countries may appear to differ widely, making direct comparisons difficult.[2]

> Assessments of the costs for managing spent fuel and radioactive waste from the civil fuel cycle are essential to establish the size of liabilities and guarantee their financing. Cost assessments are performed regularly in most countries, encompassing the various stages of the back end. However, differences across individual assessments can be quite large, making direct comparisons very difficult. Variations are attributable to disparate factors including differences in assumptions, technical solutions and national conditions.

Most expenses related to long-term waste management, and in particular to its permanent disposal, will occur long after the operations of an NPP and its income generation have ceased, hence constituting future financial liabilities. Funds have to be established to discharge such liabilities. To this end, most countries have set up financial

2. Consideration is being given at the European level to promoting harmonisation by proposing a standard itemisation of decommissioning costs, i.e. through the possible development of an "International Structure for Waste Repository Costing", as a parallel analogue to the "International Structure for Decommissioning Costing" (ISDC) for nuclear installations, recently generated through a joint IAEA-EC-NEA undertaking.

systems, in line with existing international instruments[3] and agreed principles. Notably, in accordance with the "user/polluter pays" principle, the waste producer is generally held responsible for establishing the funds. The most common mechanism of accrual is through the revenues obtained from electricity generation. Provisions accrued over the NPP lifetime are likely to be spent over very long periods of time. The payments of fees and levies are accumulated in internally or externally managed funds.

The established financial arrangements cover most existing liabilities. In most countries a segregated fund is established that is often administered by a third-party body. There is, however, considerable variability in the level of funds accumulated in different countries, with no harmonised, generally agreed approach to funding arrangements and the development of cost estimates upon which funding must be based. It should also be noted that estimation of the future cost is only one component in the determination of the funds required. Other important elements are the real rate of return of the funds, the scheduling of expenditures and the remaining NPP operational lifetime during which time fees can be levied. Given the long-term time frames, some of these elements are based on assumptions and lead to various levels of uncertainty in the economic evaluations.

As the costs for reprocessing and recycling are normally incurred while the reactors are still in operation and can thus be seen as a part of the operational cost, no segregated funds are mandated to cover such costs on a legal basis. However, in practice, operators establish funds dedicated to reprocessing.

> Expenses for disposal will appear over extended periods, with much of the expenditure occuring long after power production and income from electricity generation have ceased. It is important that appropriate financial arrangements are established and that the accrual of adequate and available funds for the eventual implementation of the selected back-end strategy is carefully pursued.

Owing to the long time frames and technical developments required (as well as other more near term aspects, such as issues in the waste characterisation, especially for legacy waste), cost calculations upon which funding needs are established are challenging and subject to significant uncertainties and potential variations over time. Cost assessments should be living tools that can evolve to reflect the developments of project scope and other potential changes as they occur. As more accurate knowledge of costs is gained through further progress in the implementation of programmes, uncertainties should gradually diminish.

Regular and comprehensive reporting and reviews of cost estimates should be undertaken, which allow for new technical knowledge and actual fund developments to be considered and for emerging shortfalls to be swiftly addressed. This is the most efficient means to ensure continued adequacy of funds.

3. I.e. the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, and the Euratom Council Directive 2011/70.

Cost estimates for future facilities, including repositories, entail many uncertainties, which will only be reduced as experience is gained in implementing the necessary infrastructure.

To verify continued fund sufficiency and to address changes, cost estimates and funding requirements are generally updated at regular intervals, taking into account new technical knowledge and actual fund developments.

Ring-fencing of funds is also a central requisite to protect funds from being used for purposes other than those intended. These important requirements are generally stipulated in most national legislations, as well as international instruments. However, segregation of funds is not always pursued in every country, and there have been cases where money collected for waste management has been employed for other uses.

Generally legal requirements also set out that funds should be managed in a low-risk manner, for example by depositing them in the national account, investing them in government bonds or following a financing strategy established by a designated body. Even these "safer" options, however, do not entirely protect against the financial uncertainties and the instabilities of national economies, as experienced in recent times, exacerbating the challenges faced by countries. Some funding systems contain further inbuilt features to suitably allocate and minimise risks. Generally, market risks are to be covered by the nuclear operator, which in some countries needs to provide securities and guarantees. For external funds, risks linked to fund performance may have to be taken by the manager of the fund. However, should unfunded financial liabilities arise (e.g. following the bankruptcy of an operator and its parent companies), it is always the state that ultimately remains responsible.

To secure the availability of funds, ring-fencing is required so that resources accrued are only used for the intended purpose. Segregation of funds is pursued by most but not all countries in their national legislations. Some funding systems contain further inbuilt features to minimise risks; for instance, in different countries securities and guarantees may be requested from nuclear operators to protect against unforeseen developments.

Recommendation 3

Governments should continue to be vigilant in ensuring that the funding systems adopted are stable and robust and that financial resources accrued by waste producers for the management of their waste will be adequate and available at the time they are needed. The following features are considered essential:

- **Regular and frequent reviews to allow for newly accrued knowledge on technical aspects and actual fund developments, as well as other qualitative factors (e.g. sociopolitical), to be taken into account and for emerging shortfalls to be swiftly addressed through the necessary corrective actions.**
- **Ring-fencing of funds to ensure that resources are only used for the intended purpose.**

5.3. Theoretical cost analysis for selected SNF management strategies

One central objective of this report has been to review the available country knowledge on the costs of the various options for the long-term management of SNF and, to the extent possible, compare estimates on a common basis. However, a direct quantitative comparison of SNF management costs in different countries was not considered to be feasible in the study, owing to differences in the types and quantities of SNF/HLW to be treated (as well as other radwaste, which sometimes is to be disposed of in the same DGR), the specificities of national regulatory and legal frameworks, the different technologies involved, and other factors. Instead, simulations of generic, theoretical cases for idealised systems were performed based on the cost information provided. A high-level static model was developed and applied to calculate full fuel cycle costs (i.e. costs per MWh including front end[4] and back end) and its breakdown, using the capital costs and O&M costs of different FC facilities as input data, together with all other parameters necessary to define the system (detailed in Sections 3.2.2 to 3.2.5). In the analysis, no consideration is given to existing legacy fuel. SNF produced exclusively from a newly built fleet of NPPs is taken into account. It was assumed that the necessary back-end facilities are deployed at the time they are needed. The input data used in the calculations (generally provided by the members of the experts group for their respective countries) were those available at the time when the analysis was performed (i.e. at the end of 2012). However, national cost assessments are subject to continuous reviews and refinements, and since that time some countries have updated (or are revising) their estimates. Although these recent estimates were not incorporated due to time constraints, changes in absolute values of some input data are not expected to significantly alter the main outcomes of this analysis, which essentially aims to identify principal cost drivers and not to determine precise absolute values. The following three fuel cycle strategies were considered:

- Open or once-through FC, with direct disposal of SNF.
- Partial recycling or twice-through FC, where REPUOX and MOX are recycled once in LWRs and then disposed of.
- Multiple Pu recycling with LWRs and FRs. This strategy contemplates single MOX and REPUOX recycling in LWRs and multiple plutonium recycling in FRs.

For the three strategies considered, calculations of levelised fuel cycle costs were performed for different values of real discount rates and different system sizes (from 25 TWh/year to 800 TWh/year), and included a detailed breakdown of FC costs as well as sensitivity analyses (as discussed in Section 3.2.7). Since low discount rates are more realistic for long-term public benefit projects, the levelised fuel cycle costs were calculated for 0% and 3% real discount rates. All calculations have been performed assuming that all nuclear reactors operate for 60 years.

From the results of the calculations, the following general findings can be drawn:

- In all strategies, the fuel cycle cost component associated with the management of SNF represents a relatively small fraction of the total levelised costs of electricity generation.
- For the reference case (defined in Chapter 3), the total fuel cycle component of the levelised costs of electricity calculated for the open fuel cycle option is lower than for the other idealised options assessed. However, differences among the three options are relatively small and within the uncertainty bands. Additional costs from reprocessing are being offset by the savings on fuel costs at the front end.
- For small systems, fixed costs are more dominant, so costs rise disproportionally as the system size decreases.
- Since specific costs decrease with the size of the system, there may be economic benefits in sharing different fuel cycle facilities between countries/utilities.

4. By including the front-end cost, recycled materials (reprocessed uranium and plutonium) in the form of REPUOX and MOX fuel and the resulting savings in the requirements of fresh uranium can also be taken into account.

The results of the FC cost calculations performed show that costs calculated for the open fuel cycle option are lower than for the other idealised options assessed. Differences among the three options in the total fuel cycle component of the levelised costs of electricity are, however, within the uncertainty bands, given the uncertainties around some input data. For the recycling options, additional costs from reprocessing are being offset by the savings on fuel costs at the front end. Differences are more noticeable if the back-end component of the fuel cycle cost is considered in isolation, since the offsetting effects are not taken into account.

It is important to note that, for all options assessed, the FC cost component associated with the management of SNF represents a relatively small fraction of the total levelised costs of electricity generation. However, these differences could translate into large absolute costs depending on the size of the nuclear programme and the period of electricity generation.

Sensitivity analyses were performed in relation to fresh UOX fuel costs, costs of different fuel cycle facilities, discount rates, FR cost premium and different implementation schedules (the latter carried out only for the direct disposal strategy):

- Uncertainties about the future costs for DGR are considerable, but their impact on the total fuel cycle cost is fairly small. As shown in Figure 3.27, a 50% increase in DGR costs (which in absolute terms would be a large sum for larger nuclear programmes) gives rise to an increase in the total fuel cycle costs by a few percentage points.
- The total cost of the nuclear fuel cycle strongly depends on the cost of fresh UOX fuel that in turns depends on the prices of natural uranium, conversion and enrichment services, as well as fuel fabrication costs. Given the uncertainty about the input data, it is difficult to accurately estimate the UOX price that renders one or the other strategy more economical. However, the calculations suggest that advanced recycling options will only be economically advantageous if the price of UOX fuel – including the price of natural uranium, enrichment services, etc. – increases significantly from the current values. This would imply an even greater increase in the prices of natural uranium, all other front-end services being equal.[5]
- In both the recycling strategies considered in this study, the second largest sensitivity after cost of UOX is the cost of reprocessing.
- The fuel cycle cost of the most advanced option *Multiple Pu recycling with LWRs and FRs* is particularly sensitive to the FR cost premium.[6] The results obtained for the reference cost scenario suggest that this advanced option would be more economical than the direct disposal route only if the FR cost premium is low (i.e. if FRs and LWRs have comparable capital and operating costs).

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5. For the same size of system of 400 TWh/year and at 3% discount rate, the multiple Pu recycling in LWRs and FRs would become attractive if the cost of fresh UOX was ~50% higher than in the reference case scenario. a system of 400 TWh/year and at 3% discount rate, the multiple Pu recycling in LWRs and FRs would become attractive if the cost of fresh UOX was ~50% higher than in the reference case scenario considered in the calculation. This corresponds to prices of natural uranium of about USD 270-300/kgU (for unchanged prices of other front-end services, e.g. enrichment, etc.) i.e. more than 100% higher than the reference assumption on the cost of natural uranium defined in this study.
6. Fast reactors are expected to be more expensive than LWRs, thus a special cost premium for their construction and operation is introduced (see Section 3.2). This extra cost is attributed to the back-end component since, in the *Multiple Pu recycling with LWRs and FRs* strategy, fast reactors (operated as burners) are considered as a means for managing the SNF.

- Overall, the uncertainties related to the full recycling option remain the greatest since only sparse data are available for these systems and no commercial system is currently operating.

Sensitivity analyses show that in all three strategies, the total fuel cycle cost is most sensitive to the cost of fresh UOX fuel, which encompasses the price of natural uranium and enrichment services. Other influential factors are:

- interim storage and deep geological repository costs in the direct disposal strategy (though a 50% increase in deep geological repository costs, which in absolute terms would be a large sum for larger nuclear programmes, gives rise to an increase in the total fuel cycle costs by a few percentage points);
- the cost of reprocessing in both recycling strategies;
- the fast reactor cost premium for the multiple plutonium recycling option.

Advanced SNF management options would be economically advantageous only if UOX fuel prices were significantly higher than current values and if FR cost premiums were low.

Recommendation 4

For countries that are committed to the ongoing use or development of nuclear energy, comparisons of the costs of different strategies for managing the back end should be drawn on the basis of the full fuel cycle cost. For countries that are phasing out or have already exited nuclear power, a direct back-end cost comparison may be more appropriate. In all cases, assessments made for total or partial FC cost comparisons should be transparent about the assumptions made and the scope of the analysis.

The assessment conducted in the study is a high-level analysis for idealised systems. Its purpose is to understand the major impacts on back-end costs of the different options and, more specifically, to identify the cost drivers. However the assessment cannot be simply transposed into a specific national context. This would require a more detailed and adapted cost analysis. In addition, we noted that the cost uncertainties related to the full recycling option are greatest, since this strategy is furthest from commercialisation.

The sensitivity analysis with respect to the implementation schedule was performed for the direct disposal of the SNF strategy, assuming delays of 20 and 50 years in the construction of the SNF encapsulation facility and DGR. Delays in the implementation of such facilities lead to extended interim storage of the SNF, and thus the escalation of the back-end component of the fuel cycle cost at a zero discount rate. This simple analysis does not take into account the possible increased degradation of SNF due to longer interim storage, which would lead to a further increase of undiscounted back-end costs. At positive discount rates, delays lead to lower back-end costs. The impact of delays is significantly smaller than the uncertainty band for the back-end costs.

5.4. Non-quantitative factors

Economics is only one of many factors influencing the decisions regarding SNF management options. It is clear that any evaluation of the comparative merits of the different back-end options will need to be considered in the specific contexts of individual countries and would not be made purely on economic grounds. The principal aim of any option considered for the long-term management of spent fuel and radioactive waste is to achieve and maintain high levels of safety, to protect individuals, society and the environment against potential hazards and harmful effects of ionising radiation over time and to take into account a broad and complex range of issues, sometimes interrelated (e.g. science and technology, safety and environmental protection, non-proliferation and safeguards, ethical and societal aspects, along with economics and finance). A discussion of some of these qualitative factors and the role they play in the evaluation and comparison of different back-end options is provided in Chapter 4 with details summarised in Table 5.1.

Alongside economic considerations, different qualitative factors come into place in the selection of back-end strategies. These encompass:

- political issues, including security of supply and non-proliferation;
- issues of an administrative, governmental infrastructural or social nature, like regulation, safety, public attitudes and transport; along with
- more technical aspects, such as environmental protection, retrievability, waste production and future technological developments.

The relative importance of these elements is intricately linked to specific national contexts and may shift over time, so that different factors may outweigh others in different countries and priorities may change with time.

Recommendation 5

In any decision-making process regarding the choice of an SNF management strategy, a multi-criteria approach should be adopted at the national level that expands the quantitative economic considerations to include qualitative factors. These can have an important (or even determining) influence in the final decision and may also have a direct impact on the costs.

It has been noted that, whatever the determining factors of a national back-end policy are, any significant shift in policy has the potential to induce considerable additional costs, which may even become dominant in the economics of any fuel cycle. This was the case with the added cost of the once-through fuel cycle in the United States, due to the cancellation of the Yucca Mountain project.

Back-end management remains one of the key challenges for the future and for the sustainability of the nuclear industry; hence countries should support the development and sharing of knowledge, experience and resources necessary for its safe, reliable and economic implementation.

Recommendation 6

Where issues of long-term fuel supply and reduction of waste volumes are particularly important (e.g. in countries with larger nuclear programmes) R&D on advanced nuclear systems, including FRs, should be supported by governments, since their implementation holds the potential for enhancing the long-term sustainability of nuclear power, notably in relation to management of waste. In this context, further engineering and cost analyses will be important to reduce the uncertainties in the costs of implementing advanced fuel cycle options.

Recommendation 7

International co-operation and sharing of experience for safe, reliable and economic implementation of back-end strategies should continue. Given the significant economic costs and expertise required for their realisation, sharing FC facilities and infrastructure would especially benefit countries with small nuclear programmes.

Table 5.1: Non-quantitative factors influencing SNF management strategy choices

Non-quantitative factors	Comment
Security of energy supply	In countries lacking internal energy resources like Japan or France, security of energy supply is a national priority. In many cases, uranium is imported, and thus interruption of supply cannot be excluded. With reduced demand for fresh natural uranium, reprocessing options enhance energy supply security even further, for example. by introducing greater technical and local diversity of facilities and services and thus broadening the resource base.
Non-proliferation	Proliferation resistance can have a profound influence on civil FC policies. The open FC is generally perceived as being more proliferation resistant. The recovery of fissile materials pursued in the basic reprocessing cycles has historically been regarded as a key vulnerability for non-proliferation. The safeguarding of reprocessing is technically demanding but is being routinely implemented. A technical option to improve the proliferation resistance of reprocessing is the prompt recycling of the plutonium produced. Proliferation concerns linked to reprocessing can be eased through the introduction of advanced reprocessing methods with no extraction of pure Pu. Multilateral approaches limiting the deployment of sensitive national facilities have also been advocated to enhance proliferation resistance.
Public attitudes	Back-end facilities are subject to societal concerns and can even provoke social dissent. Failing to obtain public support for any FC strategy can severely hamper the development of facilities and programmes or lead to considerable delays and cost increases. Regardless of the type of HLW to be disposed of, unresolved societal issues have been one of the main reasons that many DGR programmes have not proceeded as planned. Social challenges for siting reprocessing plants have also encountered public opposition, which seems more akin to that associated with nuclear power plants or front-end facilities.
Legal, regulatory and safety aspects	Safety, security and regulatory approaches (together with other principles) are embodied in legal provisions and regulations at the international and national levels. These can, however, be quite different across countries in terms of structure and the detail of legal provisions, in particular for the back end of the FC. National legislation sometimes excludes certain options, and, conversely, policy decisions on FC options can develop *de facto* normative power comparable to statutory provisions. The development of any back-end strategy entails the introduction of new facilities and technologies (whether for reprocessing, the deployment of more advanced FCs or DGRs), and legal and regulatory frameworks must be sufficiently flexible to adapt to such changes. Since, for some new technologies, regulations are not yet defined, additional effort and development of competencies will be needed for their deployment.
Environmental effects	Safety and environmental aspects are of principal concern for all FCs. For FCs with reprocessing, however, supplementary facilities add to what is otherwise part of the open FC, with the potential to increase safety, environmental and regulatory burdens. Although HLW from reprocessing undergoes reliable (and increasingly improved) conditioning (through vitrification) for long-term final disposal, concerns about the environmental impact of the operation of reprocessing plants have figured prominently in public discussions. The added radiological impact of the reprocessing option is counterbalanced by the decreased needs for natural uranium – that translates into a reduction in discharges from uranium mining and milling operations – and by the reduced footprint and long-term radiotoxicity of the ultimate waste disposed of in the DGR.
Transport	Transport of SNF/HLW can be a matter of concern to the general public. Transport represents the most exposed part of the entire FC, and as such it can become the focus of protests, demonstrating broader concerns linked to the general perception of nuclear energy and even affecting choices of SNF management strategy. Considerable investment may be needed to implement a reliable transport system, depending on the country size and its nuclear programme. The degree of influence of transportation over any FC is specific to a given situation and country and cannot be assessed in a generic way.
Waste streams	Different types of radioactive waste are generated at each step of FCs, but their relative stream volumes and timelines differ substantially depending on the FC. The advantage of reprocessing is the reduction in volume, long-term heat production and radiotoxicity of the waste that needs to be disposed of in DGRs. Taking volume and heat constraints into account a given disposal volume may take several times more HLW from reprocessing than the equivalent SNF amount. However, if reprocessing reduces the amount of HLW to be disposed of, it generates significant quantities of LILW-LL. Modern techniques and processes ensure that the combined disposal volume needed for HLW and operational waste from reprocessing is significantly less than that needed for disposal of unprocessed SNF.
Retrievability of waste	The implementation of reversibility and retrievability in a geological repository has technological implications in terms of the design of the disposal system and the associated repository infrastructure. This may yield additional costs that depend on the degree of retrievability to be achieved, the time frame over which this should apply, as well as the geological environment. If retrievability is stipulated in the national law and/or regulatory requirements, it becomes a requested attribute for the repository. Specific design features linked to reversibility and retrievability will be largely independent of the FC.
Development of fast reactors and advanced fuel cycles	Technical factors can affect the timing and costs for the deployment of back-end options and particularly more innovative ones. A prerequisite for a wider and more sustained adoption of advanced SNF recycling is the development of FRs and advanced nuclear FCs. In the past, technical problems experienced with prototype FRs, low public and political support and uncertainties in economic parameters have limited their large-scale commercial deployment. Any future transition to systems based on FRs and closed FCs is a challenging endeavour which will require careful long-term planning and infrastructure adaptation. Thus, large scale introduction of such systems is not expected to occur before the second half of this century.

Appendix 1. Details on principles and responsibilities underlying spent fuel and waste management

Principles

As introduced in Section 2.2, safety and ethical imperatives are at the root of radioactive waste and spent fuel management. Many ethical principles are defined at length in the Basel Convention (Basel Convention, 1989) and in the IAEA Safety Fundamentals[1] (IAEA, 1995). Among others, two key principles are the "intergenerational equity" and the "user/polluter pays" principles, which also raise specific financial obligations.

The **"intergenerational equity" principle** affirms that each generation that benefits from nuclear power should honour its responsibilities and should deal with its radioactive waste in a manner that protects human health and the environment, now and in the future, without imposing undue burdens on future generations.

Another ethical pillar generally integrated into the legal framework of most countries is the "**user/polluter pays" principle**, which translates into the requirement for "polluters" to build up financial means for a safe and secure disposal of the waste (NEA, 2006). A corollary to this requirement is the vital need to ensure that there is adequate funding and, thus, that mechanisms for securing funds are in place, structured and managed (e.g. to keep pace with inflation and cost escalation and, as far as possible, remain independent of the fluctuating economic climate) (NEA, 2006). The legal basis for the establishment of adequate funds relies on a number of additional important criteria (as for decommissioning, see NEA (2006), including:

- **Sufficiency** – contributions are to be in line both with the total fund collection period, and the strategy chosen;
- **Availability** – in order to ensure a level of liquidity compatible with the timetable for liabilities and their costs, the management and periodical review of funds is vital; in addition the funds are to be used only to cover the costs of the waste management obligations in line with the strategy, and not for other purposes;
- **Transparency** – funds, their accumulation, related expenses and the financial management must be transparent to the respective national authorities and other relevant stakeholders. It is also necessary that the funding system complies with national tax laws.

Stakeholder responsibilities

In a national legal and organisational framework for spent fuel and radioactive waste management the aspects typically addressed can be summarised as follows (NEA, 2010):

- the definition of the national policy and strategy;

1. The IAEA safety principles are embodied in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which can be regarded as the equivalent of the Basel Convention for hazardous wastes.

- the setting of clearly defined legal, technical and financial responsibilities for the development and operation of disposal facilities, through to any post-closure liabilities, including institutional arrangements, monitoring and means to ensure the security of the disposed waste;
- the identification of mechanisms to ensure the adequacy and security of financial provisions (e.g. through the establishment of segregated funds);
- the definition of the overall process for the development, operation and closure of disposal facilities, including the legal and regulatory requirements, the processes for decision making and the involvement of stakeholders;
- ensuring that necessary scientific and technical expertise is available to support site and facility development, regulatory review and other national review functions.

Specific stakeholder responsibilities include:

State

- **Policies** regarding radwaste management.
- **Oversight** and control for the implementation of strategies, to ensure the fulfilment of NPP owners' responsibilities for the safe and responsible management and disposal of SNF/HLW, including related licensing and environmental issues, as well as the development of criteria or guidelines for the management of funds.
- **Regulations** setting requirements for the provision of detailed and comprehensive inventory of liabilities, reliable related cost estimates and their iterative review to ensure that sufficient provisions are allocated by the responsible organisation in time to cover the future costs. In general the government ultimately approves the planning for funding, including final setting and revision of associated fees and, sometime, reference rates (e.g. in Belgium and Finland).
- Effective **legislation** and governmental frameworks (including an independent regulatory body) and infrastructures (These must also cover accident events, ensuring that adequate financial arrangements are in place for accident recovery and third party indemnification).

In addition, depending on the specific national arrangements, the government may also:

- Take over **ownership** of radwaste once this is definitively disposed of, in which case, it shall also undertake the required surveillance following the decommissioning of a nuclear or radioactive facility.
- Provide **financial resource management** of funds directly (as in the Netherlands, where the money is stored at an account at the Ministry of Finance and guaranteed by the state) or through a designated high-level organisation within the government.
- Provide **financial guarantees** in case funding systems fall short. The state may be liable of having to cover any deficiencies, if the funds are inadequate (e.g. the Netherlands).

NPP operators/radwaste generators

In compliance with internationally acknowledged principles and, in particular, the "user/polluter pays" principle generally integrated in the legal framework of most countries, radwaste generators are held fully accountable for the management and disposal of SNF/HLW. Responsibilities comprise:

- **on-site management** of radioactive waste or SNF;
- the **formulation of a strategy and plan** for their long-term management;
- treatment, conditioning, up to buffer/interim storage;
- **transport** – in general as consignor the waste generator is held accountable for the transportation for off-site management, or transfer to a disposal site;
- **bearing the costs** from production of SNF and radwaste to the end of institutional control by
- establishing segregated funds.

Waste management organisations

In most countries a responsible implementing body has been established to perform radwaste management and disposal. Such national agencies or waste management organisations can hold various responsibilities, from the centralised collection of SNF/waste and the related processing capabilities, to the final disposal. WMOs can be either state organisations, who take over the full responsibility for the technical implementation and in some cases also for funding, or organisations related to the waste generators, set up to practically implement the responsibilities of the generator. Often, it is the need to manage SNF/waste from several different producers and to deploy centralised facilities that motivates the establishment of WMOs. Private WMOs which are can help removing or insulating spent fuel management implementation responsibilities from the political process, hence favouring continuity of strategies (NEI, 2012). However, one potential issue with utility-owned WMOs may be the expansion of co-ownership, notably in the case of new utilities entering the market and requiring waste management services. For instance, negotiations are ongoing in Finland in relation to the entrance of the newcomer Fennovoima on the market.

Although WMOs are in general funded by waste producers, either directly or from state controlled funds, the boundaries of responsibilities between them and waste generators are not homogeneously defined across countries. With the input from the waste producers, the implementing body may be responsible for:

- formulating a strategy;
- maintaining inventory databases;
- elaborating cost estimates upon which appropriate arrangements for financing, fund management and its oversight are made;
- in certain cases managing the funds;
- public consultation;
- implementing long-term facilities and receiving and disposing SNF/radwaste.[2]

Some details on waste management organisations established in various NEA member countries are provided in the table below.

2. The responsibility for the management of SNF and implementation and operation of associated long-term facilities may be allocated to a separate organisation from that responsible for the LILW and decommissioning waste.

Table A1.1: Waste Management Organisations

Country	WMO	Created	Type of agency	Principal responsibilities
Belgium	**ONDRAF/NIRAS** Agency for Management of Radioactive Waste and Enriched Fissile Materials	1980	Government agency	- Entrusted by the government to manage radioactive waste and SNF. - Receives ownership of radwaste and transfer of financial means from the producer (including from decommissioning). - Revises safe technical solutions at cost price. - Passes the cost on to the producers. - Manages the fund. - Reports regularly to the Ministry of Energy and submits an annual report of its activities to Parliament. - Supervised by the Federal Agency for Nuclear Control.
Canada	**NWMO** Nuclear Waste Management Organisation	2002	Not-for-profit entity created and funded by waste producers	- Provide recommendations to the Canadian government on the long-term management of used nuclear fuel. - Implement management plan selected by the government in 2007 for the long-term management of nuclear fuel waste. - Centrally manage transportation to a central facility. - Processing into waste containers. - Remplacement underground and monitoring. - Managing and decommissioning SNF facility at the end of its life. - Ensure availability of funds (determination of funding formula). - Maintain updated cost estimates for the programme so that funding will be available when needed.
Czech Republic	**RAWRA** Radioactive Waste Repository Authority	1997	State organisation	- Radioactive waste disposal and spent nuclear fuel processing. - Preparing proposals for the determination of the scale of charges to be paid by radwaste producers. - Administering payments made by radioactive waste producers to the Nuclear Account. - Also responsible for monitoring the creation of financial reserves by licence holders for the future decommissioning of their nuclear facilities.
Finland	**POSIVA** Nuclear Waste Management Organisation	1995	Owned by nuclear power companies	Implementation of SNF disposal including: - R&D, construction, operation and closure of the repository. - Transports from interim stores to the repository.
France	**ANDRA** National Agency for Radioactive Waste Management	1991	Public industrial and commercial organisation independent of the waste producers	- Find, implement and ensure safe management solutions for all radwaste. - Propose to the Minister of Energy an evaluation of the costs relating to the implementation of such solutions. - Design, produce and manage radioactive waste storage and disposal repositories and carry out all necessary studies to this end. - Establish, update every three years and publish the inventory and location of the materials and radioactive waste. - Develop, implement and manage storage centre(s) for radwaste. - Placed under the supervision of ministers of energy, research and the environment.

Table A1.1: Waste Management Organisations *(continued)*

Country	WMO	Created	Type of agency	Principal responsibilities
Japan	**NUMO** Nuclear Waste Management Organisation	2000	Authorised by the Ministry of Economy, Trade and Industry (METI)	Implementation of final disposal including: - Selection and investigation of sites. - Construction, operation and maintenance of the repository. - Closure of the facility and post-closure institutional control. - Related research activities. - Application for budget from waste disposal fund. - Collection of contributions.
	RWMC	2000	Independent non-profit organisation	- Management and investment of the waste disposal fund and the reprocessing fund. - Checks whether the reimbursed fund (to NUMO for the Final Disposal Fund enacted in 2000 and to power utilities, for the final Spent Fuel Reprocessing fund enacted in 2005) is effectively used for final disposal operations.
Korea (Rep. of)	**KRMC** Korea Radioactive Management Corporation	2009	Government organisation	Transport, storage, and disposal of radioactive waste and SNF including: - R&D activities. - Siting, construction, and operation of facilities. - Administration of a radioactive waste management fund. Affiliated to the Ministry of Trade, Industry and Energy.
Netherlands	**COVRA** Central Organisation for Radioactive Waste	1982	Fully state owned organisation (since April 2002)	- Implementing organisation responsible for the management of radwaste and SNF. - When waste is transferred to and stored at COVRA, ownership of the waste is transferred together with the disposal fee → COVRA takes full financial responsibility for the management of radioactive waste. - Management of the capital growth fund.
Russian Federation	**NO** National Operator	Creation requested by new Federal Law (15/7/2011)	State owned	- Operating and closing of radioactive waste disposal sites. - Designing and building of radioactive waste disposal sites. - Undertaking state registration and control of radioactive substances and radioactive waste. Transfer of radioactive waste property to NO is foreseen after interim storage (limits on interim storage time and volumes are to be defined). Transfer of property of disposal sites to NO is requested by the new Federal Law (15/7/2011) by the 15 July 2013.
Spain	**ENRESA** Empresa Nacional de Residuos Radiactivos, S.A.	1984	Public company	- Safe management, storage and disposal of the radioactive waste. - Manages and administers the economic resources obtained for the financing of the functions. - Also responsible for the dismantling of NPPs and the environmental restoration of disused uranium mines and facilities. Subject to the regulatory control of the Ministry of Industry and the Nuclear Safety Council, the Committee for the Tracking and Control of the Fund for Financing of the Activities. This is an inter-ministerial committee in charge of supervising and controlling transitory investments relating to the financial management carried out by ENRESA.

Table A1.1: Waste Management Organisations *(continued)*

Country	WMO	Created	Type of agency	Principal responsibilities
Sweden	**SKB** Swedish Nuclear Fuel and Waste management Company	1970s	Owned by nuclear power companies	- Plan and implement all activities required to safely handle and dispose of the radioactive waste and SNF. - Responsible for a system of facilities used to handle all waste from the Swedish NPPs. - Regularly calculate future costs, on behalf of its owners, submitted to the Radiation Safety Authority. - SKB's owners allocate funds to the Nuclear Waste Fund.
Switzerland	**NAGRA** National Co-operative for the Disposal of Radioactive Waste	1972	Set up and owned by NPP operators and the Swiss Confederation (responsible for radwaste from medicine, industry and research).	The task assigned to NAGRA by the Swiss waste producers is to prepare and implement solutions for waste management and disposal that ensure the long-term safety of man and the environment. This includes in particular: - Preparing inventories of all radioactive waste arising in Switzerland from the nuclear power plants and from the use of radioactive materials in medicine, industry and research. - Planning deep geological repositories for all categories of waste. - Carrying out geological investigations. - Demonstrating the safety of potential sites for geological repositories. - Providing open and transparent information to the public. - Promoting international collaboration in key areas of research.
United Kingdom	**NDA** Nuclear Decommissioning Authority	2005	Non-Departmental Public Body created under the Energy Act (2004) sponsored by the Department of Energy and Climate Change (DECC)	The NDA has been given responsibility for planning and implementing geological disposal in accordance with UK government policy. This is delivered through the Radioactive Waste Management Directorate, whose objectives include: - Engage with national and local governments and communities for site selection. - Develop the specification, design, safety case and environmental and sustainability assessments for the disposal system and obtain regulatory support. - Develop and maintain an effective organisation and secure resources to deliver DGR. - Obtain and maintain stakeholder support for its activities - Deliver a focused R&D programme to support DGR and optimised packaging solutions. - NDA already provides interim storage of waste on its sites and will continue to do so for as long as it takes to site and construct a geological disposal facility.
	CoRWM Committee on Radioactive Waste Management	2003	Advisory Non-Departmental Public Body for the Department of Energy and Climate Change (DECC)	Provides independent scrutiny and advice to the UK government and ministers of the devolved administrations of Scotland, Wales, and Northern Ireland. Government set up CoRWM to consider how to manage the UK's higher activity radioactive waste in the long term, protecting people and the environment.
United States	In its final report (BRC, 2012), the Blue Ribbon Commission concluded that a new, single-purpose organisation is needed to provide the stability, focus, and credibility that are essential to get the waste program back on track. (…) The central task of the new organisation would be to site, license, build, and operate facilities for the safe consolidated storage and final disposal of spent fuel and high-level nuclear waste at a reasonable cost and within a reasonable timeframe. DOE asked the RAND Corporation to support its effort to respond to the recommendations of the BRC towards the creation of this dedicated organisation (RAND, 2012). The study considers lessons learnt from the past, it analyses different organisational models, matching them to performance goals and related critical attributes.			

References

Basel Convention (1989), *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal*, UNEP, Secretariat of the Basel Convention, Châtelaine, Switzerland. Available at www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf.

BRC (2012), *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*, United States. Available at http://brc.gov/sites/default/files/ documents/brc_finalreport_jan2012.pdf.

IAEA (1995), *The Principles of Radioactive Waste Management. Safety Fundamentals*, IAEA Safety Series No. 111-F, International Atomic Energy Agency, Vienna, Austria.

NEA (2006), *Decommissioning Funding: Ethics, Implementation, Uncertainties*, OECD, Paris, France. Available at www.oecd-nea.org/rwm/reports/2006/ nea5996-decommissioning.pdf.

NEA (2010), *Radioactive Waste in Perspective*, OECD, Paris, France.

NEI (2012), *Expert Review of Market Challenges in the Used Fuel Industry*, Nuclear Energy Insider, London, United Kingdom.

RAND (2012), *Choosing a New Organization for Management and Disposition of Commercial and Defense High-Level Radioactive Materials*, RAND Corporation, Santa Monica, United States.

Appendix 2. Spent fuel management policies and developments in different NEA countries

The table below gives a synopsis of the country choices together with some details of their evolution over time.

Country	Policy	Chronological developments
Belgium	Reprocessing	(NEA, 2011) - Mid-1970s to the late-1980s reprocessing-recycling route adopted (reprocessing contracts conducted between Synatom and Cogema). - 1993 Parliamentary debate on the suitability of reprocessing – reprocessing and direct disposal options were to be treated on an equal footing. - 1998 The Belgian government decided that no reprocessing contract may be concluded without its formal agreement. Since then, spent fuel from both nuclear power plant sites has been stored on site, using dry storage at the Doel and a wet storage pond at the Tihange site. - 1999 Moratorium on reprocessing. - Between 2000 and 2007 vitrified waste produced at La Hague as a result of the reprocessing contracts was returned to Belgium and is temporarily stored at Belgoprocess. - 2006 last MOX fuel elements loaded. - 2008, as stated in the signed multilateral convention, Synatom has fulfilled all its obligations through the repatriation of the last consignment of vitrified HLW.
Canada	Direct disposal	SNF stored at the power plant sites (in dry storage casks) until it will be disposed of: - 2002 Set up of Nuclear Waste Management Organisation. - 2007 Adaptive Phase Management programme for SNF endorsed by the government. - 2010 Initiate site selection process.
Finland	Direct disposal	SNF stored at the power plant sites until it will be disposed of: - 1983 government decision on the objectives for research and planning of nuclear waste management. - 1995 Posiva Oy set up to implement deep geological disposal. - 2000 government decision in principle on SNF disposal of existing NPPs. - 2002 government decision in principle on SNF disposal of Olkiluoto 3 unit (under construction). - 2010 government decision in principle on SNF disposal of Olkiluoto 4 unit.
France	Reprocessing	- 1991 Waste Act (known as "*Loi Bataille*") laying the general principles of radioactive waste management and research orientation. - 2006 Planning Act on the sustainable management of radioactive materials and waste. - 2007 Issue of first National Plan for the management of radioactive materials and waste (PNGMDR) by the Nuclear Safety Authority (ASN) and the General Directorate for Energy and Climate (DGEC) 2010 PNGMDR updated (based on the National Inventory of radioactive waste and recoverable materials, issued by the National Radioactive Waste Management Agency (ANDRA). (See www.oecd-nea.org/rwm/profiles)

Country	Policy	Chronological developments
Japan	Reprocessing	The basic policy: responsibility for processing and disposal of radioactive waste lies with the operators who have generated the waste. High-level waste is stored at Rokkasho facility since 1995. - 2000 Designated Radioactive Waste Final Disposal Act ("Final Disposal Act") coming into force and Nuclear Waste Management Organization of Japan (NUMO) established. - 2005 Spent Nuclear Fuel Reprocessing Fund Act enforced. - 2005 funding systems for HLW final disposal and reprocessing established. - 2007 Final Disposal Act amendment. - Following the Fukushima Daiichi accident in 2011 the policy is being reviewed. (See www.oecd-nea.org/rwm/profiles)
Korea (Rep. of)	Not decided	No final decision for the long-term management – deep geological disposal currently envisaged. - 1998 waste programme confirmed. - SNF stored at reactor sites pending construction of a centralised interim storage facility. - Research on pyroprocessing and recycling in fast reactors.
Netherlands	Planned delayed geological disposal	Final strategy still to be developed. The decision for reprocessing is left to the nuclear operator: - 1970s government policy to reprocess used SNF from both Dutch reactors. - 1984 policy for long-term (100 years) interim storage of all the country's radioactive waste and a research strategy for their ultimate disposal leading to the - Establishment of the Central Organization for Radioactive Waste (COVRA), which collects all radioactive waste produced for interim storage.

Russian Federation	Reprocessing	- 1995 issue of "The programme to the processing of radioactive waste and spent nuclear fuel, their disposal and storage for 1996-2005" in October.
		- 2007 programme prolonged with the "Federal object programme for nuclear safety and radiation protection 2008 to 2015".
		- 2011 Federal Law (No. 190-FL) on Radioactive Waste Management enacted.
		- Enforcement powers and functions conferred to "Rosatom" corporation by the Federal Law as the governmental authority in the field of radioactive waste management.
		- According to the schedule elaborated in the law:
		  - Investigations ongoing particularly in Krasnoyarsk.
		  - 2012 Decision to build an underground research laboratory (of 450-500m depth).
		  - 2025-2030 site selection based on the results of research, public debates and state expertise.
		  - Implementation of the repository in 2035 at the earliest.

Switzerland	Not decided – ten-year moratorium on reprocessing introduced in 2003	The Nuclear Energy Act of 2003 (in force since 2005) stipulates that the site selection process for both HLW and LILW repositories. - Late 1970s initial broad survey of options. - Demonstration of disposal feasibility. - 2002 Demonstration of disposal feasibility in Opalinus Clay submitted by Nagra to the Federal Council which approved it in June 2006. - 2005 Legislation enacted that stipulates site selection process for LILW and - HLW repositories through the "sectoral plan". - 2008 Approval and implementation by the Federal Council of the "sectoral plan" for site selection, after broad consultation. - 2008-2011 First stage of the "sectoral plan": potential geological siting regions suitable for the construction of safe repositories were identified and resulting list submitted to the authorities by Nagra (on behalf of the waste producers). - 2010 Broad public consultation on siting proposals. - ~2019-2020 Parliament's decision on the government's approval of the general licence for DGRs, subject to optional referendum. - Implementation of the repository in 2035 at the earliest.

Country	Policy	Chronological developments
Spain	Direct disposal	Prior to direct disposal, fuel is stored at-reactor-site, to be moved into a Centralised Temporary Storage facility (for further interim storage – site selected in late 2011). - 1984 establishment of ENRESA. - 2006 approval of the last revision of the General Radioactive Waste Plan by the Cabinet of Ministries, setting up the National Policy – the Plan contemplates several basic options. The preferred one was interim storage followed by direct disposal.
Sweden	Direct disposal	- 1970s and early 1980s policy to reprocess the fuel. - 1985 policy changed (only ~140 ton HM were reprocessed). - Present policy – direct disposal following interim storage in centralised facility - 2011 An application was made for building an encapsulation facility in Oskarshamn and a deep repository in Forsmark.
United Kingdom	Reprocessing up to 2018	- HLW from reprocessing is vitrified and stored at Sellafield. - 2001 Managing Radioactive Waste Safely (MRWS) programme initiated by the government. - 2003 Independent CoRWM set up by the government. - 2006 The government accepted CoRWM's recommendations on geological disposal, coupled with safe and secure interim storage for legacy waste. - 2007 consultation on proposals for the way in which a site would be selected. - 2008 MRWS White Paper published by the UK government (and devolved administrations for Wales and Northern Ireland), setting out a framework for implementing geological disposal for higher activity waste.* The White Paper set out that the NDA will be the implementing organisation. - 2011 proposed preliminary policy on the long-term management of the UK's civil plutonium published for public scrutiny and consultation. - December 2011 government response to public consultation indicating reuse of plutonium as MOX as the preferred solution for managing UK's plutonium stocks. - 2012 – Nuclear Decommissioning Authority confirmed their strategic position on oxide fuels which is to store spent AGR fuel that is not contracted for reprocessing, pending disposal. On the completion of current reprocessing orders, THORP will close in 2018.

United States	Direct disposal – under review	- In 1982 Nuclear Waste Policy Act (NWPA) directing DOE to develop a repository for SNF and HLW.
		- 1987 The NWPA was amended directing DOE to only evaluate the Yucca Mountain site in Nevada.
		- 2002 This was recommended, with approval by Congress.
		- 2008 DOE submitted the licence application for construction authorisation.
		- 2009 the Administration determined that Yucca Mountain was not a workable option. DOE filed a motion with NRC to withdraw the licence application for Yucca Mountain – DOE remains responsible for disposing of SNF and HLW.
		- 2010 establishment of the Blue Ribbon Commission (BRC) to evaluate alternative approaches for managing SNF and HLW from commercial and defence activities.
		- 2012 BRC final report (BRC, 2012) notes that it is too early to decide on fuel cycle option, but emphasises that site selection work for a deep repository and an interim storage facility should start urgently.
		- January 2013 waste disposal strategy announced by DOE (DOE, 2013) to address BRC recommendations, including the following timeline for the implementation of an integrated system:
		  - 2021 operation of pilot interim storage facility.
		  - 2025 operation of a larger interim storage facility.
		  - 2026 siting of geological repository.
		  - 2042 licensing of geological repository.
		  - 2048 operation of geological repository.

* The Scottish government did not sponsor the MRWS White paper and has developed its own policy which it published in January 2011, setting out that the long-term management of higher activity radioactive waste should be in near-surface facilities.

References

BRC (2012), *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*, January 2012, United States. Available at http://brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf.

DOE (2013), *Strategy for the Management and Disposal of Used Nuclear Fuel and High-level Radioactive Waste*, January 2013, Department of Energy, United States. Available at http://energy.gov/sites/prod/files/Strategy%20for%20the%20Management%20and%20Disposal%20of%20Used%20Nuclear%20Fuel%20and%20High%20Level%20Radioactive%20Waste.pdf.

NEA (2011), *Trends towards Sustainability in the Nuclear Fuel Cycle*, OECD, Paris, France.

Appendix 3. Development of deep geological repositories in different NEA member countries

Comments on progress and features

Progress of some specific country programmes is discussed in some more detail in this Appendix. Table A3.1 provides certain specific DGR features considered in some NEA member countries, including host rocks, depth, capacity and implementation of retrievability, operational period and costs, when available.

Finland and Sweden programmes towards DGR implementation have reached important milestones: a spent fuel repository design has been developed, a site selected and, for Sweden, the safety case has been submitted to the authorities. If the reviews from the safety authorities are favourable, these repositories are expected to become operational in the early to mid-2020s.

In **Sweden**, a site for deep repository was proposed in 2009, after extensive site investigations. A licence application for the encapsulation facility and deep repository was submitted in March 2011 based on a comprehensive Preliminary Safety Analysis Report (PSAR) founded on over 40 years of extensive R&D. Encapsulation and disposal is planned to start around 2025. In 2011, in order to get an international perspective, Sweden requested NEA to perform an independent review of the parts of SKB's (the Swedish Nuclear Fuel and Waste Management Company) applications covering long-term radiation safety as well as the selection of site and method. The review will supplement that of the national safety authority and serve as key input for the municipalities involved as well as other interested parties. The final report which was presented in June 2012 identified a number of possible future improvements, but found no showstoppers for the safe disposal of spent nuclear fuel.

In **Finland**, a site has been chosen for the repository and an application for construction licence was submitted to the government at the end of 2012. After setting up the objectives for research and planning of nuclear waste management in 1983, the government made subsequent stepwise decisions in principle concerning the disposal of SNF. The construction of an Underground Rock Characterisation Facility began in 2004. Operations of the repository are expected to commence around 2020. A current open issue in Finland is the waste management plan for the new unit to be built by Fennovoima. The positive decisions-in-principle made by the government in 2010 includes a condition by which Fennovoima must present to the Ministry of Employment and the Economy either an agreement regarding nuclear waste-related co-operation with the current nuclear management custodians or an assessment programme on the environmental impacts of its own final disposal facility for spent fuel. The Ministry of Employment and the Economy appointed a working group in March 2012 to steer nuclear power companies' joint investigation of the alternatives available for final disposal of nuclear fuel. The task of the working group was to collect existing material for comparison of alternatives, to perform preliminary comparison of the final disposal alternatives if necessary, and to give recommendations for further work. Information regarding building two separate facilities and the current state and expansion of the planned facilities is required in order to compare final disposal alternatives. The work was completed at the end of 2012. In the final report the working group found that experience from Posiva's work should be used when aiming at an optimal spent fuel management solution irrespective of the number of repositories. They recommended that the companies continue negotiations towards a solution for Fennovoima's spent fuel management.

In **France**, deep geological disposal is formally defined as the reference solution for high-level and long-lived radioactive waste, and target dates for licensing and opening the repository are set respectively for 2015 and 2025. Waste disposed of is to be retrievable during the operation of the DGR. The site was selected in 2010 in a clay formation, at the boundary between the Meuse and the Haute-Marne districts. Research is currently on-going for the development and demonstration of technologies, especially at the Bure URL. The next milestones are:

- 2013 → public debate;
- "By the end of 2013/beginning of 2014: finalisation of cost estimation and design selection start of preliminary design phase";
- 2015 → submission of safety case for licence application;
- 2016 → law on retrievability;
- 2019 → start of construction;
- 2025 → start of operation, depending on the decision of the authorities.

Research is ongoing mainly in the underground rock laboratory, in clay rock formations, at Bure, eastern France.

In **Belgium**, activities are proceeding with the definition of a conceptual design and the development of safety and feasibility studies, whose first submission to the safety authorities is intended by 2013. Licence to build is expected in 2032 and the assumed in-service date is 2047 for co-disposed long lived LILW and around 2090 for HLW.

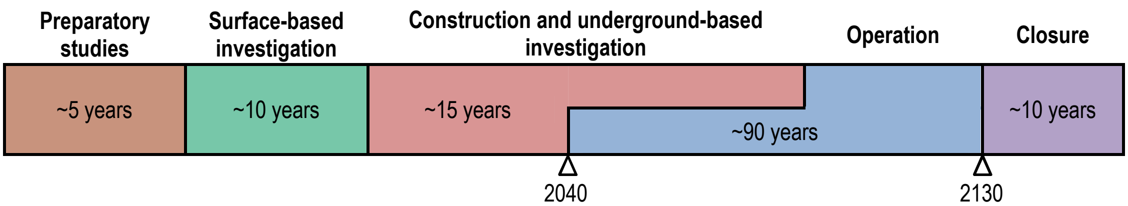
In **Canada**, in line with the Adaptive Phase Management Program for the management of SNF, a siting process is currently underway to find suitable candidate communities in acceptable geologic locations with the intent of selecting a willing host community for a deep geological repository. Collaborative engagement and communication with people across the country have been ongoing for several years. The target in-service date is 2035.

In the **Netherlands**, while a definitive strategy has not yet been defined, geological disposal of radioactive waste and SNF is foreseen, after long interim storage (at least 100 years) above ground. A tentative schedule for implementation (under development) envisages a decision on disposal to be taken in 2080, site selection in 2115 and disposal between 2130 and 2170. The choice for long time interim storage in the Netherlands was well considered, based on the small Dutch nuclear programme and low amounts of waste produced, and not taken as a "wait and see" option.

In the **Russian Federation**, a Federal Law (No. 190-FL) for the management of radioactive waste was enacted the 11 July 2011. Within the scope of this law a schedule was elaborated, according to which a site for a deep geological repository should be selected between 2025 and 2030 with the implementation of the repository expected at the earliest in 2035. Currently there are three final disposal projects for HLW being investigated. Extensive investigations for the site exploration have been ongoing at the site Mayak (Chelyabinsk) since 1975 and at Krasnoyarsk (Nishnekansker granite massif with the sites of Verchne-Itatski) since 1990. More recently another site has been considered (with investigation starting in 2000) at the Priargunsk mine (in the Chita region). In the Nishnekansker granite massif an underground laboratory for the investigation of interactions between the waste and the surrounding rocks and environmental effects is planned for construction. However, Krasnoyarsk site is currently considered as the most suitable site and an underground research laboratory of

450-500 m depth is planned for construction by 2021. Depending on the results of relevant research and public discussion, the ultimate selection of the DGR site should be finalised between 2025 and 2030.

In the **United Kingdom**,[1] a framework for implementing geological disposal for higher activity waste is set out in the Managing Radioactive Waste Safely White Paper, published in 2008. The process to site a facility will be staged, with six subsequent steps envisaged; the first three are focussed on the identification of the geological disposal site based on voluntarism and partnership with local communities, while the remainder will involve successive phases of investigation leading to final selection, construction and operation, as depicted below.



For planning purposes, it is assumed that the decision to begin Stage 6 of the siting process (construction and underground based operations) could be made from around 2025. At this time local authorities are being invited to participate in the site selection process. The White Paper also set out that the Nuclear Decommissioning Authority will be the implementing organisation, responsible for planning and delivering the geological disposal facility. The Nuclear Decommissioning Authority (NDA) already provides interim storage of waste on its sites and will continue to do so for as long as it takes to site and construct a geological disposal facility.

In **Japan**,[2] a stepwise site selection and characterisation process for a retrievable disposal site is underway and is expected to be completed by 2025, and to start operation from 2035. In the first step, Preliminary Investigation Areas are to be selected on a nationwide scale. This was commenced in December 2002 with an open solicitation by the Nuclear Waste Management Organization (NUMO) for municipalities to investigate the areas as potential candidate sites. Only one prefecture (Toyo-Town of Kochi) submitted an offer for the start of a preliminary investigation in 2007, but this was subsequently cancelled. In a second step, and on the basis of the results of the Preliminary Investigations, areas will be selected for detailed surface-based investigations, followed by the selection and investigation of a potential disposal site using underground facilities. Vitrified residues from reprocessing operations conducted in France and in the United Kingdom are being returned to Japan by sea. According to Japanese utilities the transport of such waste is expected to continue for at least ten years, at a frequency of one or two shipments per year. High-level waste has been stored at Rokkasho facility since 1995 and an interim storage facility designed to store SNF and HLW above-ground is under construction in Mutsu. Underground laboratories are under construction at Mizunami in crystalline rock and at Horonobe in sedimentary formations.

1. See: Radioactive Waste Management Programmes in OECD/NEA Member Countries United Kingdom: www.nea.fr/rwm/profiles/UK_profile_web.pdf.
2. See: Radioactive Waste Management Programmes in OECD/NEA Member Countries Japan: www.nea.fr/rwm/profiles/Japan_profile_web.pdf.

In **Switzerland**,[3] legislation that came into force in 2005 stipulates that the site selection process for both HLW and LILW repositories be defined in a so-called "sectoral plan" procedure. Site selection should be based primarily on technical criteria, with the main emphasis on safety, but must also address land use planning and socio-economic aspects. The plan approved in April 2008 following a broad consultation process, defines a three-stage site selection process and a series of site selection criteria as well as the respective roles and responsibilities of the parties involved. Stage 1 focuses on the identification of suitable siting areas based on safety and geological criteria. In October 2008, Nagra (on behalf of the waste producers) submitted a list of potential geological siting areas to the authorities (three main areas for the HLW repository), with consideration to a "combined repository" (LILW and HLW). Reviewed and approved by relevant groups, Nagra's proposals were subject to a broad public consultation process in late 2010. Stage 2 of the sectoral plan process includes a number of activities that will be undertaken in close collaboration with the siting regions involved and that will allow the identification of at least two sites each for the HLW and LILW repository. In Stage 3 of the process, the remaining sites will be investigated in depth with a view to site selection and finalisation of the repository projects together with the siting regions. Stage 3 will lead to the submission of applications for a general licence (one for each HLW and LILW or one for a so-called "combined repository"). Parliament's decision on the government's approval of the general licence for DGRs is expected around 2019/2020 and will be subject to an optional national referendum. A deep geological repository for high-level waste is expected to be ready for operation in 2045 at the earliest.

3. See: Radioactive Waste Management Programmes in OECD/NEA Member Countries, Switzerland: www.nea.fr/rwm/profiles/Switzerland_profile_web.pdf.

Table A3.1: DGR features considered in some NEA member countries

Country	Host rock(s) considered	Depth (m)	Capacity	Retrievability	Operational period	Cost			Other
						Overnight investment	O&M	Total	
Belgium[1]	Boom clay	250-300	5 334 tHM[2]	Still under discussion.	~60 years	HLW: USD 1 481 M (EUR 1 016 M) LILW-LL: USD 2 082 M (EUR 1 428 M)	HLW: USD 335 M (EUR 230 M) LILW-LL: USD 529 M (EUR 363 M)	HLW: USD 1816 M (EUR 1 246 M) LILW-LL: USD 2 611 M (EUR 1 791 M)	
						Including encapsulation costs			
Canada	Crystalline (sedimentary rock also considered)	~500	108 000 tHM[3]	No – allowances for possible recovery.	135 years	USD 3 836 M	USD 10 581 M	USD 14 417 M	
Czech Republic	Granitic rock	~500	Up to 10 000 tHM	No	~85 years	USD 917 M	USD 1 546 M	USD 2 463 M	
Finland	Crystalline	~400	5 500 tHM[4]	Considered as an option.	96 years	USD 802 M	USD 918 M	USD 1 720 M	Closure costs: USD 277 M
France	Clay	~500	HLW 7 000m^3 LILW 70 000m^3	Yes – legal requirement Deep disposal should be reversible for at least 100 years.	~100 years				
Korea (Rep. of)	TBD	TBD	PWR 22 500 tHM	TBD	50 years	USD 4 430 M	USD 1 416 M	USD 5 846 M	Closure costs: USD 230 M
			CANDU 11 500 tHM			USD 902 M	USD 623 M	USD 1 525 M	Closure costs: USD 43 M
Netherlands	Boom clay, rock salt	TBD	SNF(RR): 60 m^3 Vitrified: 100 m^3 HLW: 800 m^3	All hazardous waste that cannot be treated otherwise must be disposed of in a retrievable way.	25 years	USD 2 649 M (USD 2 000 M)	To be assessed		Overnight investment includes transfer of waste, development and D&D of RWM facilities.
Russian Federation	Granite (Krasnoyarsk region – Nizhne Kansky massif)	450-500	Vitrified HLW 11 250 tHM HLW+LL ILW – up to 150 000 m^3	Currently not envisaged.					

Table A3.1: DGR features considered in some NEA member countries *(continued)*

Country	Host rock(s) considered	Depth (m)	Capacity	Retrievability	Operational period	Cost			Other
						Overnight investment	O&M	Total	
Spain	Granitic rock, clay, rock salt	TBD	7 000 tHM[5]	Still under discussion.	14 years	USD 1 192 M	USD 993 M	USD 2 185 M	
Sweden	Granitic rock	~470	12 000 tHM	Not legal requirement, but considered possible Stepwise implementation with reversibility in each step.	50 years	USD 2 553 M	USD 1 665 M	USD 4 218 M	Closure costs: USD 277 M
United Kingdom	[6] Different geological environments considered for planning purposes: - higher strength rock; - lower strength rock; - evaporites.	TBD – likely to be somewhere between 200 m-1 000 m), depending on the geology of the site.	[7] Co-location of HLW, ILW and LLW considered: - 11 200 m^3 SNF - 1 400 m^3 HLW[8] - 364 000 m^3 ILW - 17 000 m^3 LLW - 3 300 m^3 Pu - 80 000 m^3 U according to Baseline Inventory	[7] Still under discussion The NDA RWMD will develop a flexible design for geological disposal that has the potential to be maintained in a retrievable mode and is encouraging waste packagers to manufacture waste packages with the appropriate longevity.		[6] If it is assumed that the baseline inventory, as set out in the Managing Radioactive Waste Safely White Paper (but excluding plutonium and uranium) is to be included in the concept then the cost is in the order of GBP 12 billion (at 2008 money values and undiscounted; i.e. ~USD_{2010} 19 283 M[9] Cost estimates for implementing a design concept in higher strength rock and in an evaporate rock. If the same inventory is assumed to be included in a concept for lower strength rock then the indicative costs would be expected to increase by around GBP 4 billion (i.e. ~USD_{2010} 6 427 M – see note above).[10]			
United States	TBD	TBD	TBD	**Yes** – Legal requirement. However, the new strategy set by DOE (DOE, 2013) concluded that retrievability it is not necessary for purposes of future reuse.					

1. Conversion factor used for costs: 0.686 from EUR 2009.
2. HLW 4 118 canisters = 742 m^3, ILW 657 m^3, LILW-LL ~12 500 m^3.
3. The capacity may vary between 86 400-172 800 tHM.
4. Maximum capacity according to government decision and construction licence application up to 9 000 tHM.
5. Including ~20 000 FAs + 1 000 m^3 of ILW-LL.
6. Source: www.nda.gov.uk/documents/upload/Frequently-Asked-Questions-related-to-Geological-Disposal-July-2012.pdf.
7. Source: http://mrws.decc.gov.uk/assets/decc/mrws/white-paper-final.pdf.
8. Equivalent to 2 900 t of conditioned but not packaged HLW (see NDA, 2007, UK RW Inventory report, page 35-36: www.nda.gov.uk/ukinventory/documents/Reports/upload/The-2007-UK-Radioactive-Waste-Inventory-Main-Report.pdf).
9. Assuming an average yearly inflation index of 2% and a conversion factor to USD_{2010} of 0.647179.
10. The increase in cost for a lower strength rock facility is because the underground openings have to be smaller than for the other rock types and, as a result for the same waste inventory more openings would be required. On top of this there are additional costs to support and maintain the infrastructure and emplacement facilities and extra equipment required.

Appendix 4. Financial arrangements adopted by different NEA member countries

The table below summarises the financial arrangements adopted by different NEA countries highlighting some of their key features.

Key features of financial arrangements in NEA countries	
Belgium	
Method	NPP owners have full responsibility for SNF/HLW management and disposal – Synatom (subsidiary of Electrabel) is responsible for establishing nuclear provisions on behalf of the nuclear licensee (Electrabel) and of companies having shares in nuclear electricity production (stipulated by the law). Payments to Synatom are made by the nuclear licensee Electrabel (and, indirectly, by the companies having shares in nuclear electricity production) on a quarterly basis. Commission on Nuclear Provisions formally approves any changes in methodology, funding or investment policy. ONDRAF/NIRAS provides unanimous advice on the Conclusions of the Commission with respect to the sufficiency of financial provisions. ONDRAF/NIRAS manages the fund in order to finance long-term duties, in particular the disposal of the waste. Costs related to the activities of ONDRAF/NIRAS will be charged to those who benefit from the performed services. Contributions for fixed and variable costs are Individually defined for each waste producer. For instance, contributions to cover fixed costs are based on the average of waste transferred to ONDRAF/NIRAS in the previous five years and that planned for transfer in the subsequent five years.
Scenario(s)	Based on plant operation limited to 40 years, and full reprocessing option.
Fee	Not provided.
Adjustment	Three-year reviews.
Securities	Contractual guarantee: each of the main producers commits to paying in the long-term fund the balance of the fixed costs attributable to the waste that has not yet been covered by tariff payments. If planned volumes are reviewed by the producer to higher values, the guaranteed sum would be increased accordingly (and other producers' guarantees correspondingly decreased).
Back-loan	A percentage of the provisions can be lent back to the nuclear licensee (back-loan; currently, up to 75% of the provisions).
Decommissioning*	Synatom is also responsible for decommissioning provisions – decommissioning fund appears separately in their annual accounting. However, how far these "two funds" are managed separately is not clear.
Release of responsibilities	At the end of the contractually agreed period, or in case the waste producer would terminate the relationship with ONDRAF/NIRAS before the end of the term, the waste producer must pay in full its outstanding share of the fixed costs.

Key features of financial arrangements in NEA countries	
Canada	
Method	Federal government responsible for developing policy, regulating the safe management of waste, and for overseeing waste owners' implementation of solutions for managing their own waste – as stated in the Canada's 1996 Radioactive Waste Policy Framework. **Body responsible for the implementation** The Nuclear Waste Management Organization, a federal not-for-profit entity created and funded by the waste producers, will centrally manage transportation of the waste to a central facility, its processing into waste containers, emplacement underground and monitoring, managing and decommissioning SNF facility at the end of its life. **Waste generators** Waste owners are responsible for funding, managing and operating waste management facilities in a safe and secure manner. The legislation also requires the owners of the waste to pay for the full lifecycle costs of managing the waste over the long term. - The overriding principle of radioactive waste management in Canada is that it is the owners of the waste who are responsible for implementing and funding its safe and secure long-term management. - Annual contributions required up to 2035 (year the DGR becomes operational). - To fund 100% of the post construction licence costs of the SNF programme. - Part of annual amount to fund fixed costs of programme, part to deal with variable costs (new production). - OPG has internally calculated a Levelised Unit Electricity Cost type value for the cost per kWh over the life of the nuclear program and has estimated it at CAD 0.1189 cents/kWh. **The Nuclear Safety and Control Act**, administered by Canada's independent regulator – the Canadian Nuclear Safety Commission – is a legislative framework for regulating the use of nuclear energy and materials to protect the health, safety, and security of Canadians and the environment.
Scenario(s)	30-year deferred dismantlement strategy.
Fee	CAD 0.1189 cents/kWh internally calculated by OPG over the life of the nuclear programme.
Adjustment	Annually based on the expected returns of the various producers segregated funds. Every five years, costs are rebaselined and the fee for the committed and variable portion are subject to change.
Securities	Financial Guarantees to the nuclear regulator (CNSC) are required by any facility that has radioactive waste.
Decommissioning*	No
Release of responsibilities	Owners of NPPs 100% accountable to handle and load waste into containers for dry fuel storage and ultimately into transport containers for travel to a central SNF repository.
Czech Republic	

Method	Levy on electricity generated in NPPs:
	- **Government** controls the nuclear account and funds may only be used through RAWRA for tasks specified in the Atomic Act.
	Conditions for the investment of nuclear account funds on the financial market are stipulated by the Atomic Act under the supervision of the Ministry of Finance (revenues and interest accrued are fed to the account).
	Payments from the state budget cover the cost of management of radioactive waste deposited as per regulations in force prior to the Atomic Act.
	- Radioactive **waste generators** pay into account through:
	  - one-off payments;
	  - payments in instalments;
	based on an assessment of services provided for radwaste disposal or SNF processing and disposal.
	The account also includes paid services provided by RAWRA, grants and payments from abroad (IAEA, EU projects).
	- **RAWRA** administers payments to the nuclear account and prepares documentation on the level of payments.

Scenario(s)	40 years operation of NPPs. Deferred decommissioning strategy.
Fee	CZK 0.05
Adjustment	Five years – In case of discrepancies, a government decree is issued to modify the level of payments.
Decommissioning*	No

Key features of financial arrangements in NEA countries	
Finland	
Method	**Objective**: at each moment there shall be sufficient funds available to take care of the remaining nuclear waste management (NWM) measures caused by the waste produced up to that moment. Payments to the fund are based on liabilities which are regularly estimated. The Fund does not pay for the NWM measures but keeps in safe the money corresponding to the costs of the remaining measures. All the funds are returned to the operators when they have carried out all the necessary NWM operations.
Scenario(s)	For funding calculations operation of the NPPs is assumed to end at the end of the year in question.
Fee	Not applicable.
Adjustment	- Capital of the Fund adjusted annually. - Additional contribution from licence holders (if necessary). - Repayments from the Fund to the operators are also possible.
Securities	The part of liability that is not covered by money in the Fund must always be guaranteed by full securities. 10% additional securities for unforeseen costs.
Back-loan	The waste generators (nuclear power plant operators) may borrow back up to 75% of the accumulated funds.
Decommissioning*	Yes
Release of responsibilities	NPP owners are responsible for radwaste management until it has been disposed of in a manner accepted by the authorities. All the funds are returned to the operators when they have carried out all the necessary NWM operations.
France	
Method	French **waste producers** remain responsible for radwaste management and are financing all the related costs (including R&D made by ANDRA). Producers are required by the 2006 law to follow rules ensuring a prudent financial management of a segregated fund dedicated to finance all the related costs linked to produced radwaste (including HLW). **ANDRA** is responsible for the R&D on the long-term behaviour of radwaste in DGR (to ensure proper confinement by the clay layer), facility construction & operation. ANDRA activities are financed by French producers. Moreover, orphan nuclear facilities are under the responsibility of ANDRA which is using governmental funds for this purpose. **Government** is establishing (together with all involved parties) the national policy for the management of nuclear materials and waste (PNGMDR) and following its implementation with the help of experts (checking the scientific progress made) through the National Evaluation Commission. This policy is regularly evaluated by an advisory committee of the French Parliament in charge of scientific and technological issues (OPECST). The funding level is supervised by governmental authorities (DGEC) and by the Financial Evaluation Commission (CNEF), which includes experts and representatives from the French Parliament. The safety authority (ASN) also provides support and expertise to the government for this task. **Reprocessing** No segregated fund legally necessary for reprocessing. However in practice EDF operates a fund dedicated to reprocessing.
Scenario(s)	40 years of waste/SNF production.
Decommissioning*	No (but includes some waste from NPP decommissioning)
Release of responsibilities	French waste producers remain responsible for nuclear waste & SNF forever.

Key features of financial arrangements in NEA countries	
Japan	
Method	- The **state** (Ministry of Economy, Trade and Industry) establishes the basic policies and direction regarding final disposal; engages with local residents to get assent; defines the final disposal plan, including time and quantities to dispose of; designates, authorises and supervises bodies for the implementation of the plan and the management of the funds. - **NPP owners** have full responsibility for SNF/HLW management and disposal. - Funding systems for HLW final disposal and for reprocessing, etc. were enforced in 2005. A fee is levied on the electricity bill for the systematic accumulation of funds for the final disposal of vitrified radwaste. A different fee is raised to feed a separate fund for reprocessing. - **The Nuclear Waste Management Organization of Japan** (NUMO) is the body designated for the implementation of the final disposal plan, also responsible for collecting contributions from utilities. - **Radioactive Waste Management Funding and Research Center** is the body designated for managing the Final Disposal Fund as well as the Reprocessing Fund.
Scenario(s)	40 years, 30 years, 16 years (legal useful life).
Fee	Not available
Adjustment	Contributions are reviewed by the government annually.
Korea (Republic of)	
Method	- Annual lump-sum payment per SNF assembly produced in the year, based on a cost estimate and considerations of discount rate and inflation. - The funds can be invested in government and public bonds and are used for expenses related to Radwaste management, including R&D. - **Government** sets the fees after a proposal by - **KRMC** (Korea Radioactive waste Management Cooperation) manages the radwaste fund.
Scenario(s)	30-40 years NPP operating life. Decommissioning 10 years. Dismantling 3 years.
Fee	Not provided
Adjustment	Two years – the government can adjust the fee.
Decommissioning*	No – NPP Decommissioning costs are left as internal reserves of NPP utility, applying the annual allowance deposit method inside NPP utilities, based on decommissioning costs per reactor unit.
Netherlands	
Method	Reprocessing costs implicitly covered in electricity prices (NPP). Charges on reception of all radioactive waste, i.e. spent fuel (RR), vitrified and technological waste HLW as well as LILW (NPP), and industrial and medical LLW. All radwaste and SNF to be transferred to COVRA. A capital growth fund is established for future maintenance and disposal of the waste. **Waste producers** have to pay in advance for all present and future costs. The money to cover future costs is accumulated in a separate capital growth fund. **COVRA** (fully state owned) is responsible for radwaste and SNF management, including the capital growth of the fund. **Government** – the money is stored at an account at the Ministry of Finance and guaranteed by the state.
Scenario(s)	Interim storage above ground in engineered structures allowing retrieval at all times, for a period of at least 100 years.
Fee	Not provided.
Adjustment	Five years – basis for the cost estimate reassessed. In case of inadequate fund growth the fees for waste are adjusted.
Securities	Money of fund guaranteed by the state. As COVRA is fully state owned, eventually the state will have to cover any deficiencies.
Decommissioning*	No
Release of responsibilities	All radwaste and SNF to be transferred to COVRA. Waste producers have to pay in advance for all present and future costs.

Key features of financial arrangements in NEA countries	
Russian Federation	

Method	**State governing body** in RWM
	Enforcement powers and functions:
	- Enforcement of storage facilities ownership;
	- State radioactive waste account and control including registration of storage facilities;
	- Approval of forecasted radioactive waste projected inventories;
	- Accounting of funds gathered in special reserve;
	- Funding of radioactive waste disposal activities;
	- Registration of fees received from organisations radioactive waste-producers into a special reserve, and registration of the radioactive waste volume transferred by them for burial.
	- Approval of radioactive waste interim storage time limits;
	- Proposal on the establishment of the national operator
	- National Operator activities control;
	- Proposal on tariffs for radioactive waste disposing;
	- Definition of regulation for radiation control of disposal sites during post-closure;
	- Proposals to government on:
	  - the design, siting, building, operation, closure and decommissioning of federal storage facilities;
	  - identification of potential sites for: disposal, long-term storage facilities, as well as storage of special radwaste.
	National operator
	- Develop radioactive waste projected inventories;
	- Develop radioactive waste disposal programme;
	- Develop general scheme of radioactive waste disposal sites and transport logistics;
	- Build, operate and close radioactive waste DGR(s);
	- Receive radwaste for disposal, ensuring that acceptance criteria are met;
	- Deduct part of fees from "non-nuclear organisations" to special reserves;
	- Monitor and ensure safety of radioactive waste disposal sites during their entire operation period, including periodic radiation controls after closure;
	- Provide information to stakeholders.
	Specialised organisations
	- Legal entity, responsible for the collection, sorting, treatment, conditioning, transportation, storage operation and decommissioning (or closure) of storage facilities (chapter 2 of FL-190).
	Owners of NPPs
	- Own radioactive waste and is responsible for its safety until transfer of ownership to National Operator for final disposal.
	- Provide safe interim storage and condition the radwaste prior the end of the interim storage period (limited to five years).
	- Transport radwaste to national operator.
	- Financing of disposal (before the end of the interim storage period) by making quarterly payments into a special reserve on the basis of tariffs.

Key features of financial arrangements in NEA countries	
Russian Federation *(continued)*	

	TO BE DEFINED
	A new Federal Law (No. 190-FL) on Radioactive Waste Management was enacted in July 2011 defining:
	- New enforcement powers and functions to "Rosatom" corporation as governmental authority in the field of radioactive waste management, including responsibilities:
	  - to develop proposals on National operator creation to the Russian government;
	  - to establish provisions to fund radioactive waste disposal.
	- New radioactive waste categorisation:
	  - Accumulated – radioactive waste, formed before the day of entry into force of the Federal Law;
	  - Newly generated – after entry into force of the Federal Law;
	  - New classification – six classes on the basis of the disposal method required.
	- Ownership of radioactive waste:
	  - radioactive waste, formed before the entry of law in force – federal property;
	  - radioactive waste, formed after the entry of law in force – producer's property.
	- Ownership of radioactive waste disposal sites:
	  - Disposal sites may be property of the federal government or the "Rosatom" corporation;
	  - Transfer of property of radioactive waste disposal sites to the National Operator – before 15 July 2013.
	- Funding:
	  - Producers ought to pay for disposal of newly generated radioactive waste;
	  - Revenue from irregular deductions of non-nuclear organisations for radioactive waste disposing.

Release of responsibilities	Radwaste producers own radwaste and are responsible for their safe treatment and conditioning (in line with acceptance criteria) prior to termination of interim storage and transfer of ownership to the national operator for final disposal. The national operator is responsible for safe radwaste management after documented receipt of radioactive waste. The property of existing disposal sites is to be transferred to the national operator before 15.07.2013 (chapter 41 FL-190). The property of newly implemented disposal facilities is to be transferred under national operator within one year after commissioning (chapter 41 FL-190).
Spain	
Method	**State** The management of radwaste, including SNF, and the dismantling and decommissioning of nuclear facilities is an essential public service – to be provided by the state. The Tracking and Control Committee, attached to the Ministry for Industry, Energy and Tourism Trade (MINETUR), responsible for the supervision, control and qualification of transitory investments. **Body responsible for the implementation** ENRESA (Empresa Nacional de Residuos Radiactivos, S.A.) is commissioned by the government to manage this public service. ENRESA provides radwaste management services for the NPP operators and radioactive facilities, governed by contracts subject to the approval by the Ministry of Industry, Tourism and Trade. **Owners of NPPs** – The prime responsibility for the safety of waste management is with the licensee. Contracts with ENRESA for the provision of radwaste management services establish the terms, which extend to the end of the service lifetime of the installations, including the dismantling of nuclear facilities and, where appropriate, of radioactive facilities, and the payment to be made, where applicable, for the services to be rendered. Costs of managing radwaste are financed through the so-called Fund for the financing of activities included in the General Radioactive Waste Plan, which is fed with revenues from fees, including the financial yield generated by them. Fees include: 1. A fee relating to the electricity tariff (tolls) to finance costs for the management of radwaste and SNF generated at those NPPs permanently shut down prior to 1 January 2010. 2. A fee levied per kWh produced for licensees to finance all costs incurred as from 1 January 2010 and corresponding to the management of radwaste and SNF generated from NPP operation, regardless of the date of generation, along with costs for D&D. 3. Fee relating to the Juzbado Fuel Assembly Manufacturing Facility. 4. Fee relating to other facilities (CIEMAT or other companies, e.g. medicine, industry, agriculture and research). In all these cases the costs are applied directly at the moment of rendering of the services.

Key features of financial arrangements in NEA countries	
Spain *(continued)*	
Scenario(s)	40 year service lifetime Complete dismantling strategy (Level 3) for the LWR NPPs, to be initiated 3 years after definitive shutdown. (In the case of Vandellós 1 NPP, complete dismantling on completion of the dormancy period.)
Fee	Fee 2 EUR 0.669 cts/kWh (for NPPs in operation since 01/2010)
Adjustment	**Annually** ENRESA submits during the first six months of every year: an updated economic-financial study of the costs of the activities contemplated in the General Radioactive Waste Plan, including payment for plan management activities and the suitability of the financial mechanisms in force with respect to such costs.
Securities	As ENRESA is fully state owned, eventually the state will have to cover any deficiencies.
Decommissioning*	Yes
Release of responsibilities	The state takes over the ownership of radwaste once definitively disposed of. It also undertakes the required surveillance following the decommissioning of a nuclear facility. All radwaste and SNF to be transferred to ENRESA. Waste producers have to pay in advance for all present and future costs.
Sweden	
Method	- Owners of NPPs have the full responsibility to cover all costs for waste management. - Each NPP owner pays (individually set) fees into segregated funds. - Fee levied per kWh produced. - Annual fee also for shutdown reactors to cover possible lack of funding. - SKB provides a comprehensive cost calculation of all future costs. - SSM assesses the correctness of the calculation, considers additional costs for licensing and public involvement, as well as future inflation and expected return on capital in the funds and proposes the fee. - Government sets the fees after a proposal by SSM. - Separate authority (Kärnavfallsfonden – Nuclear waste fund) controls and manages the fund.
Scenario(s)	based on: - 40 years operation of NPPs; - direct disposal after ~40 years of interim storage; - early dismantling of the NPPs.
Fee	Average of ~SEK 0.021/kWh (range SEK 0.020- 0.024/kWh) for 2012.
Adjustment	Three years (annually up to 2008)
Securities	NPP owners have to provide securities to cover unforeseen developments, etc.
Decommissioning*	Yes
Release of responsibilities	NPP owners are only relieved of their implementation and payment responsibilities when all waste has been safely disposed.

Key features of financial arrangements in NEA countries	
Switzerland	
Method	- According to the "user/polluter pays" principle, the costs of disposal are to be sustained by the waste generators and are covered through a fee on the price of electricity. - Contributions that operators must pay to the funds for NPP decommissioning and the fund for the management of radioactive waste as well as the provisions they have to put in place are calculated on the basis of a detailed estimate of costs for waste management, which must be conducted every five years. - Cost projections provide overnight costs (and do not include uncertainty margins).They are based on best estimates – relying on the most recent knowledge and clear temporal development of events. - Owners of NPPs have the full responsibility to cover all costs for waste management. - Each NPP owner pays (individually set) fees into segregated funds. - Fee levied per kWh produced. - Fund Commission responsible for cost estimates. Cost calculations are commissioned to Swissnuclear and their verification is conducted by ENSI (the Swiss national regulatory) on behalf of the committee.
Scenario(s)	50 years operation of NPPs. Five years of post-operational phase. Followed by decommissioning (complete dismantling expected some 15-20 after shut down).
Fee	~0.8 to 0.9 cents CHF/kWh (reference year 2011)
Adjustment	Five years.
Securities	Operators have to provide securities for a sum equivalent to the paid contributions (increased by the interest and reduced from charges).
Release of responsibilities	NPP owners are only relieved of their management responsibilities when the waste is placed in a deep repository and the financial resources required for the monitoring phase and the possible closure are ensured.
United Kingdom**	
	Government is responsible for the policy, will take final decisions and engage with stakeholders to ensure that the objectives of the radwaste programme are met. The NDA is the implementing organisation, responsible for R&D, planning and delivery of the geological disposal facility and, as part of this process, will engage with communities and other stakeholders. The NDA already provides interim storage of waste on its sites and will continue to do so for as long as it takes to site and construct a geological disposal facility. CoRWM provides independent scrutiny and advice to government on the plans and programmes for delivering geological disposal including interim storage. It also develops the baseline inventory. The long-term management of higher activity radwaste through geological disposal will apply to all waste owned by: (i) the NDA; (ii) private companies producing HLW, including both the nuclear and non-nuclear sectors; (iii) Ministry of Defence (MoD). It will be for operators in categories (ii) and (iii) above to negotiate appropriate commercial contracts with the NDA for emplacement of their waste in the geological disposal facility. Operators of new nuclear power stations are required to have a Funded Decommissioning Programme (FDP) approved by the Secretary of State before nuclear-related construction can begin. Alongside the approval of an Operator's FDP, the government will expect to enter into Waste Contract with the Operator regarding the terms on which the government will take title to and liability for the Operator's spent fuel and ILW. In particular, this agreement will need to set out how the price that will be charged for this waste transfer will be determined. The Waste Transfer Price will be set at a level consistent with the government's policy that Operators of new nuclear power stations should meet their full share of waste management costs.

Key features of financial arrangements in NEA countries	
United States	
Method	**Owners of NPPs** – Fee on nuclear electricity generated and sold. **State** DOE is responsible for the management and disposal of the radioactive waste (HLW, LLW, and TRU) and SNF it owns or generates and for regulating DOE radioactive waste disposal facilities except as otherwise provided by law. DOE is also responsible for the disposal of SNF and HLW generated by commercial activities. DOE has regulatory authority over health, safety, and environmental protection regarding radioactive waste generated at its facilities. In January 2013, the DOE announced a new waste disposal strategy (DOE, 2013) elaborated by the administration to address recommendations from BRC (BRC, 2012). This calls for legislative authorisation by Congress and the enactment of a new legal framework (e.g. to reform the current funding arrangement and to establish a dedicated waste management organisation.
Fee	1 mill/kWh (USD .001 per kWh)
Adjustment	annually - no change to initial method or charge to date.
Decommissioning*	Yes

* This column considers whether NPP decommissioning costs are included in an overall fund.

** Source: UK MRWS, 2008.

References

BRC (2012), *Blue Ribbon Commission on America's Nuclear Future: Report to the Secretary of Energy*, United States. Available at http://brc.gov/sites/default/files/ documents/ brc_finalreport_jan2012.pdf.

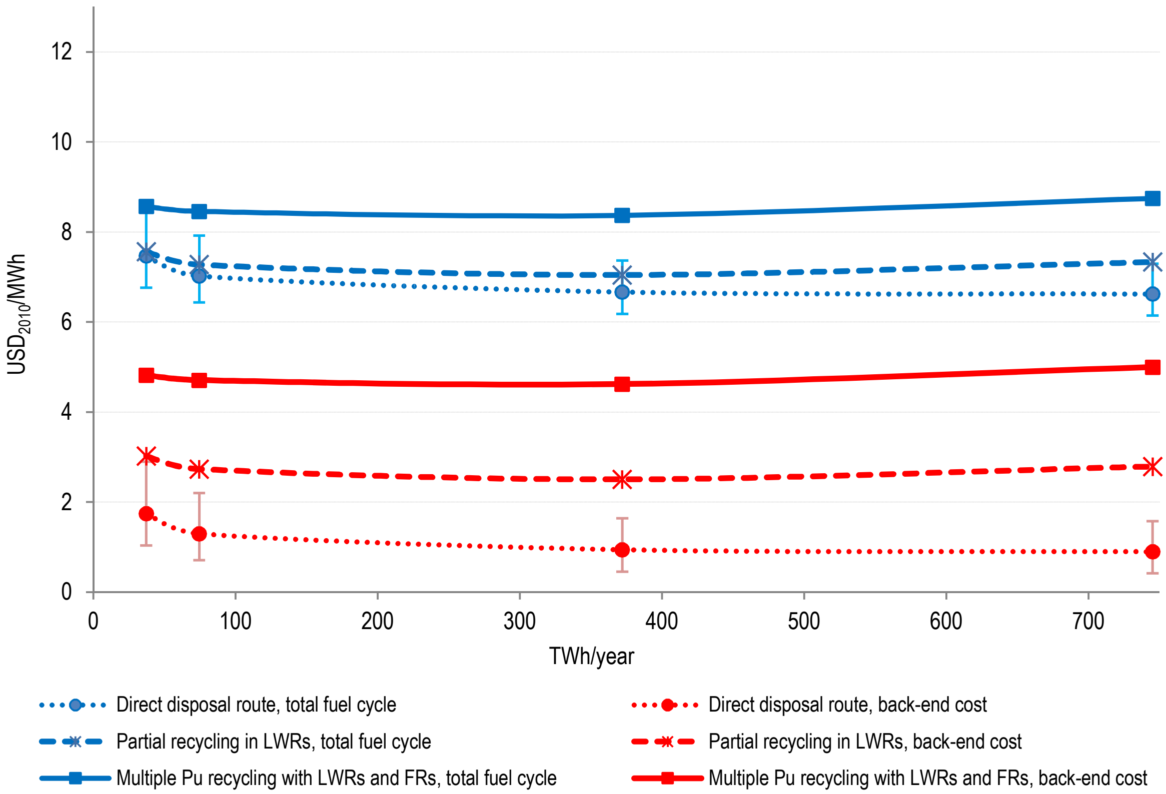
DOE (2013), *Strategy for the Management and Disposal of Used Nuclear Fuel and High-level Radioactive Waste*, Department of Energy, Washington DC, United States. Available at http://energy.gov/sites/prod/files/Strategy%20for%20the%20Management %20and%20Disposal%20of%20Used%20Nuclear%20Fuel%20and%20High%20Level%20Radioactive%20Waste.pdf.

UK MRWS (2008), *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal*. A White Paper by Defra, BERR and the devolved administrations for Wales and Northern Ireland.

Appendix 5. Fuel cycle costs at 7% discount rate

Figure A5.1: $LCOE_{Fuel\ cycle}$ and $LCOE_{Back\text{-}end}$ for different reactor fleets and back-end strategies*

(7% discount rate)

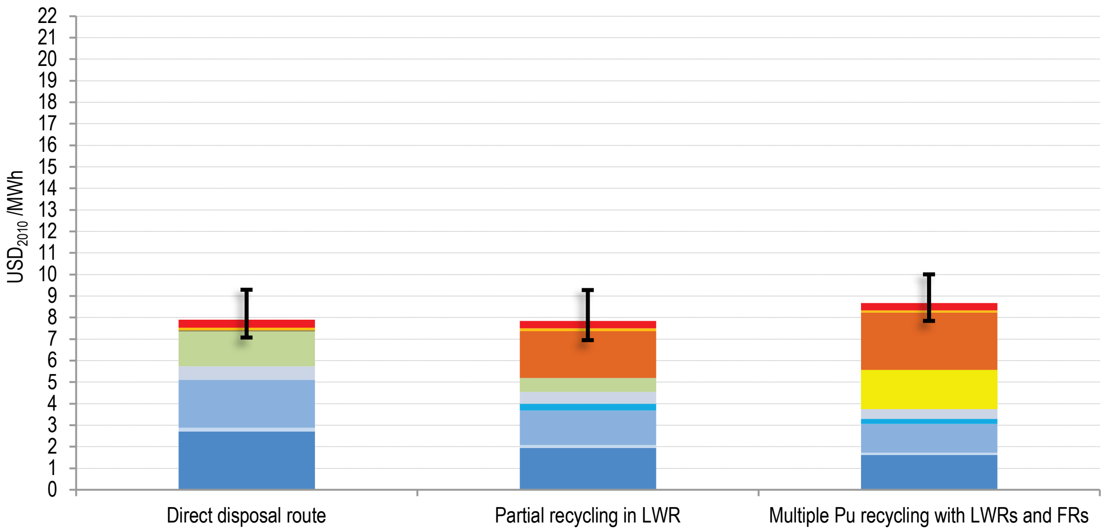


Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

* Uncertainty bands are only plotted for the direct disposal case. Similar bands apply to the other options, as shown in Figures 3.23 to 3.26.

Figure A5.2: Fuel cycle cost breakdown for different strategies and system sizes, in the reference cost level scenario, at 7% discount rate

(25 TWh/year system)



(75 TWh/year system)

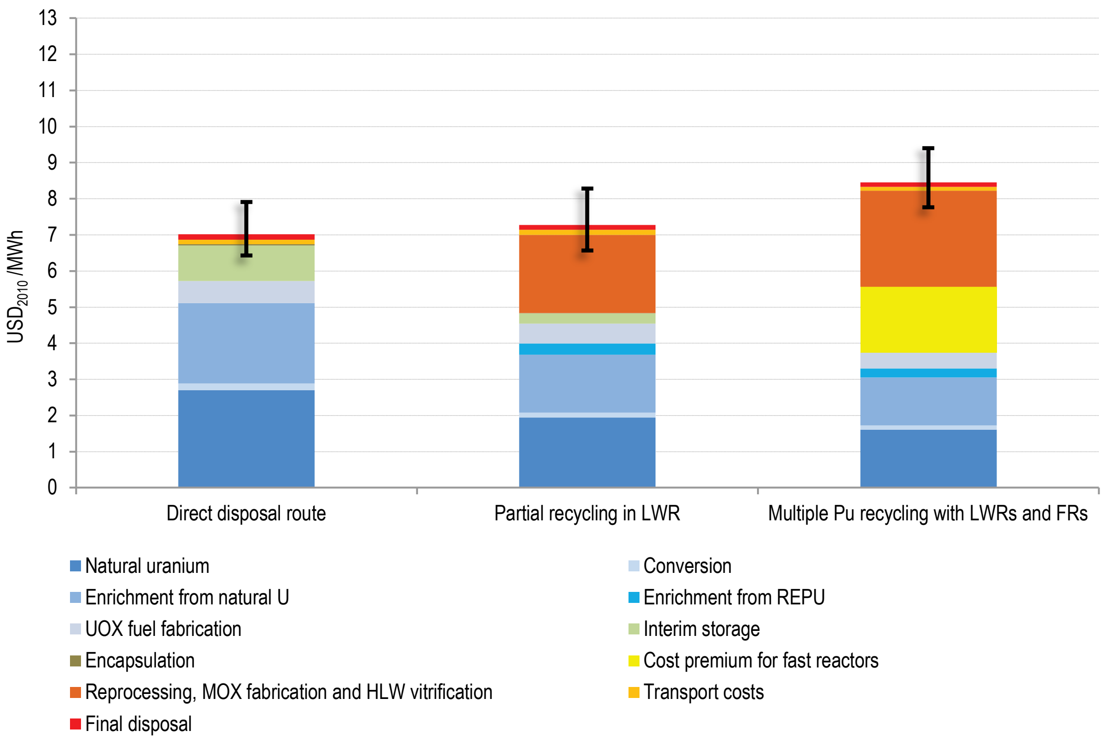
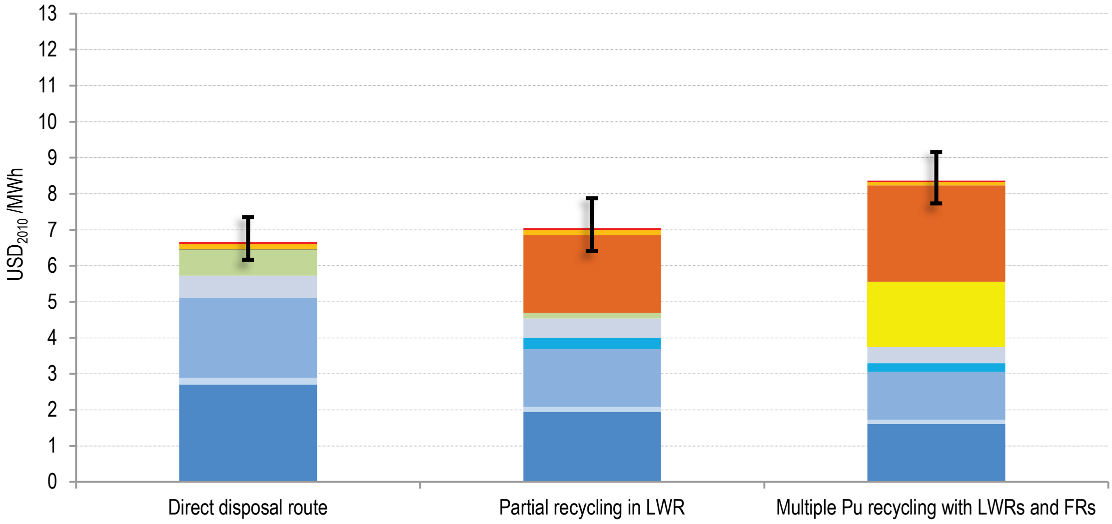
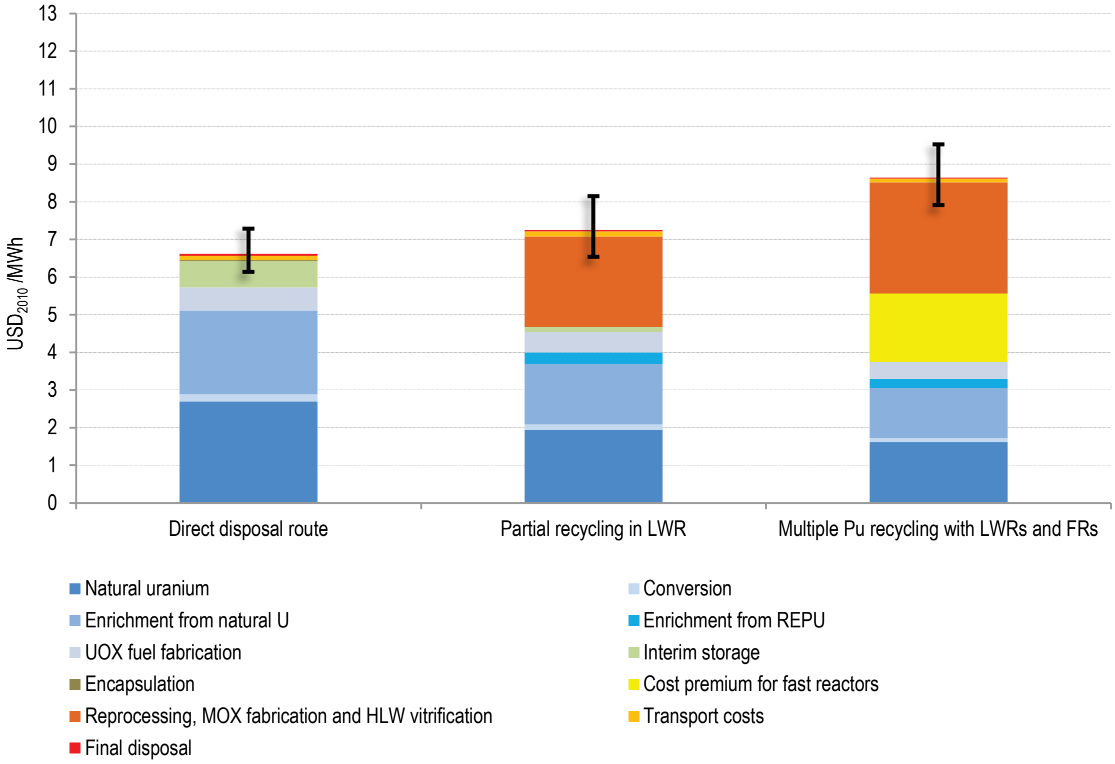


Figure A5.2: Fuel cycle cost breakdown for different strategies and system sizes, in the Reference cost level scenario, at 7% discount rate *(continued)*

(400 TWh/year system)



(800 TWh/year system)



Note: The central values represent the results from the reference cost scenario, and the error bars correspond to the low and high cost scenarios.

Appendix 6. Comparison of results of existing economic models

This Appendix provides further details on the comparative appraisal of existing economic models undertaken in Section 3.3. The models reviewed in Section 3.3 are listed in Table A6.1, together with some of the primary modelling discriminators. The methodologies and models used to produce the calculations are important to the granularity and composition of the outputs produced in the analysis.

Analysis methodology – some important elements include:

- Calculations of LCOE vs. equilibrium costs. In the MIT study (MIT, 2011), a new method for deriving an LCOE produced fuel cycle costs that are 4-15% lower than the results from equilibrium cost calculations. At low conversion ratios (CR = 0.5) the effect is small (4%) but increases in step with the conversion ratio; i.e. CR = 1.0 nets a 13% higher cost, and CR = 1.23 nets a 15% cost difference.
- Economic analysis that uses the time value of money (e.g. present worth analysis) will increase the relative contribution and importance of early schedule lead items such as the construction of MOX fabrication plants and reprocessing capacities and will decrease the relative costs for lag items such as waste conditioning and disposal, especially at high discount rates. Additionally, the benefits netted from payments for fuel services may be heavily discounted in future years.

Modelling environment – modelling software may range from very simple (e.g. Excel spreadsheets) using commercial off-the-shelf software to customised software:

- Spreadsheet models produce costs on a static cost basis.
- Dynamic analysis using system dynamics software provides a different perspective from the static equilibrium analysis typically performed with spreadsheets. The initial start-up flows generated by dynamic models are generally in non-equilibrium. Under these conditions, the fraction of fast reactors in time will be much lower than predicted by simple static equilibrium calculations because of multiple system constraints that impact the amount of TRU available for fuelling new reactors at start-up. Therefore, the total costs during the start-up period (say, first 50 years) for the closed fuel cycles will be lower than the static costs.
- Advanced fuel cycle simulation codes can analyse fissile material flows and radioactive decays from fuels and waste. Reactor physics codes may be coupled to the models to determine the radioactive content over time and tracking of decay heat and radiotoxicity.

The economic input data used in the model calculations are key to the modelling results. The nominal cost inputs used in the models for the fuel cycle front end (uranium, conversion, enrichment, fabrication, depleted uranium disposal), back end (fuel storage and disposal, HLW disposal) and recycling (product storage, reprocessing, MOX and TRU fuel fabrication) are provided in Table A6.2. The unit cost data are the original figures used in the studies based on the base date of the study. The nominal unit cost data are presented in raw form without normalisation.

Table A6.1: Methodology and modelling environment differences

Methodologies	G4 ECONS	VISION/ VISION.ECON	MIT (2011)	NEA (1994, 2006)	Rothwell (2011)	Harvard (2003)	BCG (2006)	Oxford (2011)
Analysis methodology								
Levelised cost vs. equilibrium	Equilibrium	Equilibrium	LCOE (new)	Equilibrium	Equilibrium	Equilibrium	Equilibrium	Equilibrium
Present worth				PWA	PWA		PWA	PWA
Modelling environment								
Software	Excel, DPL	System dynamics	Excel	Custom/ Excel	Excel, MC sim.	Excel	Excel	Excel+ others
Static vs. dynamic	Static	Dynamic	Pseudo-dynamic	Static	Static	Static	Static	Static
Reactor physics analysis	External	Internal and external	External	External	External	External	External	External

Table A6.2: Cost comparison between the fuel cycle unit costs in different studies

Fuel cycle description	Units	AFCI (2009)	MIT (2011)	NEA (1994)	NEA (2006)	Rothwell (2011)	Harvard (2003)	BCG (2006)	Oxford (2011)
		Nominal							Low-High
Base year of monetary units		2008	2007	1991	2006	2011	2003	2006	2011
Front end									
Natural uranium	USD per kgU	60	80	50	50	110	40	80	30-70
Conversion (natural)	USD per SWU	10	10	8	5	11	6	12	10-30
Enrichment (natural)	USD per kgU	105	160	110	100	130	100	110	100-180
UOX fuel fabrication	USD per kgU	240	250	275	250	275	250	200	150-300
Depleted uranium disposition	USD per kgU	10	10			6.56	6		
Back end									
Interim dry storage UOX	USD per kgHM	120	200	150	150		200	150	
Geological disposal of spent UOX	USD per kgHM	1 000	470	610	610*	225	400	700	405-2 025
Geological disposal of spent MOX	USD per kgHM		3 130			940		2 240	
Geological disposal of reprocessed waste	USD per kgHM			90	90*		200		
Geological repository (HLW FPs + Ln + Tc)**	USD per kgFP	10 000	3 650						
Recycling									
Recycled U/TRU product storage	USD per kgHM	200			300				
UOX reprocessing	USD per kgHM	1 000	4 000	720	1 000	2 500	1 000	630†	
LWR MOX fuel fabrication	USD per kgHM	1 950	2 400	980	1 250	2 701	1 500		
Fabrication of FR metal fuel	USD per kgHM	2 500	2 400		2 600		1 750		

* 1991 data;

** Ln = Lanthanum; Tc = Technetium.

† Integrated plant.

A summary of the fuel cycle cost differences between models is provided in Table A6.3. These non-normalised costs show the raw variation in costs resulting from using different models, economic inputs, methodologies, and assumptions. The studies are ordered (top to bottom) from the most recent to the oldest, with the Oxford study and BCG study separated since they use different cost bases than the other studies.

Table A6.3: Fuel cycle cost differences across models (non-normalised)

Study (study year)	Once-through cycle	Twice-through cycle	Advanced reprocessing
AFCI (2009) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **2.64** (40%) 6.51	 **N/A** N/A	Weighted costs* **5.78** (70%) 8.22
MIT (2011) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **1.30** (15%) 8.40	 **2.89** (29%) 9.98	Ranges **3.37-4.42** (32-38%) 10.46-11.51
NEA (1994) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **0.76** (14%) 5.46	 **1.53** (25%) 6.23	 **N/A** N/A
NEA (2006) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **~1.40** (29%) ~4.80	 **N/A** ~5.50	 **N/A** ~6.00
Rothwell (2011) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **1.13** (15%) 7.66	 **6.78** (53%) 12.71	 **N/A** N/A
Harvard (2003) -Back-end cost (USD/MWh) -Total FC cost (USD/MWh)	 **1.50** (32%) 4.74	 **2.80** (47%) 6.00	 **3.50** (52%) 6.74
BCG (2006) -Discounted unit - Net present cost (NPC)	 USD 500/kgHM -USD 47-50 B	 USD 520/kgHM -USD 48-53 B	 N/A
Oxford (2011) -Net present cost (NPC)	Scenario 1: -GBP 2 515 M	Scenario 2: -GBP 1 812 M Scenario 3: -GBP 3 100 M Scenario 4: -GBP 2 454 M	N/A

* AFCI costs are weighted based on a system composed of 75% LWRs feeding separated actinides from reprocessed LWR fuel to ABRs (25% of system) operating on a closed cycle.

N/A = Not applicable.

The first six studies (AFCI, 2009; MIT, 2011; NEA, 1994 and 2006; Rothwell, 2011; and Harvard, 2003) produce fuel cycle costs on a levelised unit cost basis. Back-end fuel cycle costs for the once-through cycle range from 15% to 40% of the total fuel cycle costs, primarily differing by the assumed costs for SNF disposal. Back-end costs for the twice-through cycle range from 29% to 53% of total fuel cycle costs as a reflection of differences in UOX reprocessing costs, MOX fuel fabrication, and HLW disposal costs. The back-end costs for advanced processing range from 32% to 70% at least in part due to differences in fast reactor fuel fabrication costs.

BCG discounted costs for the once-through strategy, where used fuel is disposed directly into a geological repository after a 25-year period of interim storage, is ~USD 500/kgHM (USD 320/kgHM for the repository and USD 180/kgHM for interim storage and transportation). The discounted unit cost of a recycling strategy is ~USD 520/kgHM.

The main cost component is construction and O&M of the integrated recycling plant (USD 525/kgHM), while transport costs (USD 75/kgHM) and HLW-R disposal (USD 80/kgHM) are offset by credits from recycled fuel (USD 160/kgHM).

Oxford NPV results show that Scenario 2 (conversion of legacy Pu into MOX fuel) are lower than Scenario 1 (storage and waste disposition only) due to income from MOX fuel sales (cost of reprocessing is not included in the analysis and the Pu is already separated), but has higher initial spending because of early MOX plant investment. Scenario 3 (including the reprocessing of AGR fuel) is not competitive because the cost of refurbishing and operating THORP is higher than the assumed discounted cost of AGR becoming a waste. Scenario 4 (adding overseas fuel for processing) begins to be competitive as reprocessing income compensates for THORP costs.

In summary, this benchmarking review conducted compared eight existing studies (and associated cost models) for the calculation of the back end of the nuclear fuel cycle, in terms of their calculation methods, assumptions, key input parameters and outputs. Emphasis was primarily placed on the nuclear fuel cycle costs for the closed fuel cycle in comparison to direct used fuel disposal. To summarise some of these major cost points, the following four questions are addressed:

What major cost factors are associated with the back end of the nuclear fuel cycle?

The major back-end fuel cycle cost factor in the open fuel cycle is geological disposal. For closed fuel cycles (twice-through and advanced cycles) the major cost factors are fuel reprocessing, HLW disposal, MOX and FR fuel fabrication, and waste conditioning processes. For closed cycles, the waste conditioning (e.g. vitrification) determines the loading of the high-level waste form (which can range from two to ten times relative to SNF loading). The radioactive constituents remaining in the waste coupled to the waste-loading factor, significantly impact the required size of the geological repository.

Where are the largest uncertainties in the cost factors?

Some typical fuel cycle costs and uncertainty data are reported from the AFCI study on advanced fuel cycle economic analysis of symbiotic LWR and FR systems (Shropshire *et al.*, 2009a). This study performed a cost sensitivity analysis on two closed fuel cycle systems, where the derived cost and uncertainty data, as provided in Table A6.4, are illustrative of those found/used in many of the fuel cycle models.

Table A6.4: Illustration of cost uncertainties for back-end fuel cycle technologies

Fuel cycle technology	Fuel cycle cost	Cost uncertainty range
UREX+ separation	USD 1.5/MWh	± USD 1.00/MWh
Electrochemical separation/metal fuel fab	USD 1.5/MWh	± USD 0.75/MWh
HLW repository	USD 1.0/MWh	± USD 0.50/MWh
HLW/ILW/LLW conditioning	USD 0.8/MWh	± USD 0.40/MWh
MOX fuel fabrication	USD 0.5/MWh	± USD 0.25/MWh
Managed decay storage (Cs/Sr)	USD 0.4/MWh	± USD 0.20/MWh

Cs = Cesium; Sr = Strontium.

Table A6.4 shows that reprocessing technologies have the highest fuel cycle cost contribution to the total cost of electricity and also have the highest cost uncertainty. Other key fuel cycle costs include: HLW disposal in a deep geological repository; HLW/ILW/LLW conditioning; MOX fuel fabrication; and decay storage.

How do the total costs of the reprocessing option compare to the direct disposal option?

For the majority of the twice-through fuel cycle studies (MIT, 2011; NEA, 1994 and 2006; and Harvard, 2003), the fuel cycle cost premium for using a MOX closed fuel cycle ranged from 14-25% over the cost of a once-through cycle using direct disposal. It is notable that in the BCG study the costs for closing the fuel cycle were only 4% higher than the cost of direct disposal. The two other extremes included:

- Oxford (2011) estimated that given conditions in the United Kingdom, reprocessing legacy Pu and used fuel results in 28% lower cost than for direct disposal. This result is not surprising since the cost of reprocessing is not included in the analysis and the Pu is already separated.
- Rothwell *et al.* (2011) estimated the twice-through costs at 66% higher than direct disposal.

What about the costs of advanced fuel cycles versus existing cycles?

Based on the findings from the advanced fuel cycles (AFCI, 2009; MIT, 2011; NEA, 2006; and Harvard, 2003); the fuel cycle cost premium for using a fast reactor closed fuel cycle ranges from 25-42% over the cost of the once-through cycle using direct disposal. Additional costs resulting from any cost premium on fast reactors would also need to be factored into the costs of using advanced fuel cycles. Also, country-specific requirements as well as the recycling technology maturity should be considered when defining the appropriate fuel cycle costs that are applicable to their applications.

To place these costs in perspective, the fuel cycle costs typically constitute less than 20% of the LCOE for nuclear energy. If closing the fuel cycle results in 25% higher fuel cycle costs, then the cost of electricity would increase by less than 5%. If fast reactors are required, then any premium on their costs would be additional to the fuel cycle cost increase. In nuclear systems consisting of 25% fast and 75% thermal reactors, AFCI found that closed fuel cycles employing advanced technologies would increase the cost of nuclear-generated electricity by only 5–6 mils (~10%), but that the cost uncertainties are large.

In conclusion, according to the studies reviewed in this section, closing the fuel cycle results in somewhat higher costs than for direct disposal. Beyond economics, countries may still prefer this option for reasons of increased energy security, improved resource sustainability, as a hedge to future uranium cost increases or scarcity, to reduce demands for geological repository space, to decrease the environmental or health risks of long-lived radioactive waste, for the creation of new commercial capabilities to reprocess used fuel and fabricate MOX, to decrease stores of used fuel at reactor sites, or for other reasons.

References

BCG (2006), *Economic Assessment of Used Fuel Management in the United States*, Boston Consulting Group report, Boston, United States. Available at: www.bcg.fr/documents/file15203.pdf.

Oxford (2011), *A Low Carbon Nuclear Future: Economic Assessment of Nuclear Materials and Spent Nuclear Fuel Management in the UK*, Smith School of Enterprise and the Environment, Oxford, United Kingdom.

Rothwell, G., *et al.* (2011), "Option values for the long-term use of MOX", a working paper submitted to Energy Policy, for the International Atomic Energy Agency, Vienna, Austria.

Bunn, M., *et al.* (2003), *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, DE-FG26-99FT4028, Cambridge, MA, United States.

De Roo, G., and J. Parsons (2011), "A methodology for calculating the levelized cost of electricity in nuclear power systems with fuel recycling", MIT Nuclear Fuel Cycle Study, *Energy Economics,* Cambridgem MA, United States, Vol. 33, pp. 826-839.

NEA (1994), *The Economics of the Nuclear Fuel Cycle*, OECD, Paris, France.

NEA (2006), *Advanced Nuclear Fuel Cycles and Radioactive Waste Management*, OECD, Paris, France.

Shropshire, D.E., *et al.* (2009a), "Advanced fuel cycle cost basis 2009", Idaho National Laboratory report INL/EXT-07-12107 Rev. 2., United States. Available at: www.inl.gov/technicalpublications /Documents/45367 00.pdf.

Shropshire, D.E., *et al.* (2009b), *Advanced Fuel Cycle Economic Analysis of Symbiotic Light-Water Reactor and Fast Burner Reactor Systems*, INL/EXT-09-15254, Idaho, United States.

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Appendix 8. List of acronyms and abbreviations

AFCI	Advanced Fuel Cycle Initiative
AGR	Advanced gas-cooled reactors
ALARA	As low as reasonably achievable
BRC	Blue Ribbon Commission
CoRWM	Committee on Radioactive Waste Management
CR	Conversion ratios
D&D	Decommissioning and dismantling
DGR	Deep geological repositories
DOE	Department of Energy (US)
EIA	Environmental impact assessment
FC	Fuel cycle
FP	Fission products
FR	Fast reactor
GDP	Gross domestic product
GIF	Generation IV International Forum
HLW	High-level waste
IAEA	International Atomic Energy Agency
ILW	Intermediate-level waste
LCOE	Levelised cost of electricity generation
LILW	Low- and intermediate-level waste
LL	Long-lived
LLW	Low-level waste
LWR	Light water reactor
MA	Minor actinides
MOX	Mixed oxide
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NPP	Nuclear power plant
OECD	Organisation for Economic Co-operation and Development
OVC	Overnight investment costs
O&M	Operation and maintenance

PPP	Purchase power parity
Pu	Plutonium
PUREX	Plutonium and uranium extraction
PWR	Pressurised water reactor
R&D	Research and development
REPUOX	Reprocessed uranium oxide
SL	Short-lived
SNF	Spent nuclear fuel
THORP	Thermal Oxide Reprocessing Plant
TRU	Transuranics
U	Uranium
UK	United Kingdom
UOX	Uranium oxide
US	United States
VLLW	Very low-level waste
WIPP	Waste Isolation Pilot Plant
WMO	Waste management organisation

Units

Billion	1 000 million
G	Giga = 10^9
K	kilo = 10^3
M	Mega = 10^6
T	Tera = 10^{12}
GWa	Gigawatt-year
GWd	Gigawatt-days
GWe	Gigawatt electric
kg	Kilogramme
kgU	Kilogrammes of uranium
KWh	Kilowatt-hour
m	Metre
manSv	Man sievert
MWe	Megawatt electric
MWh	Megawatt-hour
SWU	Separative work units
t	Tonnes
tHM	Tonne of heavy metal
tU	Tonnes of uranium
TWh	Terawatt-hour

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The Economics of the Back End of the Nuclear Fuel Cycle

The feasibility and costs of spent nuclear fuel management and the consequent disposal of ultimate waste continue to be the subject of public debate in many countries, with particular concern often expressed over the lack of progress in implementing final disposal. Uncertainties about back-end costs and the financial risks associated with management of the back end have also been singled out as possible deterrents to investment in new nuclear power plants.

This report offers an appraisal of economic issues and methodologies for the management of spent nuclear fuel and high-level waste from commercial power reactors. It includes a review of different back-end options and current policies and practices, with a focus on the cost estimates for these options and the funding mechanisms in place or under consideration in OECD/NEA countries. A generic economic assessment of high-level estimates of back-end cost impacts on fuel cycle costs is undertaken for selected idealised scenarios, by means of a simple static model. Sensitivity analyses are conducted for the evaluation of uncertainties in major components and the identification of cost drivers. Since factors other than economics are an important part of the decision-making process, an analysis of the influence of key qualitative parameters in the selection of back-end strategies is also presented in this report.

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