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Techno-economic Comparison of Geological Disposal of Carbon Dioxide and Radioactive Waste

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TECHNO-ECONOMIC COMPARISON OF GEOLOGICAL DISPOSAL OF CARBON DIOXIDE AND RADIOACTIVE WASTE

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The reduction of greenhouse gas emissions is an important prerequisite for sustainable development. The energy sector is a major contributor to such emissions, which are mostly from fossil fuel fired power plants acting as point sources of carbon dioxide (CO_2) discharges. For the last twenty years, the new technology of carbon capture and storage, which mitigates CO_2 emissions, has been considered in many IAEA Member States. This technology involves the removal of CO_2 from the combustion process and its disposal in geological formations, such as depleted oil or gas fields, saline aquifers or unmineable coal seams.

A large scale energy supply option with low CO_2 emissions is nuclear power. The high level radioactive waste produced during nuclear power plant operation and decommissioning as well as in nuclear fuel reprocessing is also planned to be disposed of in deep geological formations.

To further research and development in these areas and to compare and learn from the planning, development and implementation of these two underground waste disposal concepts, the IAEA launched the coordinated research project (CRP) Techno-economic Comparison of Ultimate Disposal Facilities for Carbon Dioxide and Radioactive Waste. The project started in 2008 and was completed in 2012. The project established an international network of nine institutions from nine IAEA Member States, representing both developing and developed countries.

The CRP results compared the geological disposal facilities in the following areas: geology, environmental impacts, risk and safety assessment, monitoring, cost estimation, public perception, policy, regulation and institutions.

This publication documents the outcome of the CRP and is structured into thematic chapters, covering areas analysed. Each chapter was prepared under the guidance of a lead author and involved co-authors from different Member States with diverse expertise in related areas. Participants drew on the results of earlier research, specific case studies in the relevant fields and on the background material collected by the IAEA in preparation for this CRP. The content of the chapters was reviewed and discussed at three research coordination meetings and was further developed after the formal termination of the CRP. The comparative studies on radioactive waste and CO_2 disposal have shown that there are a number of differences and some similarities in all thematic areas from which both communities can learn.

The IAEA officers responsible for this project and publication were F.L. Toth and N. Barkatullah of the Office of the Deputy Director General in the Department of Nuclear Energy.

CONTENTS

SUMMARY

Global climate change is a major challenge for humanity. The dominant greenhouse gas (GHG) is carbon dioxide (CO_2) that contributes more than 70% to the global GHG emissions. About 40% of the total CO_2 emissions result from electricity generation, due to the overwhelming reliance on fossil fuels, especially coal.

There is a widespread consensus that global emissions of CO_2 have to be considerably reduced in order to stabilize its concentration in the atmosphere and thereby mitigate climate change. The required reductions can be realized by various types of measures, including:

- Energy efficiency improvements and reduction of the energy demand;
- Use of low carbon energy sources, such as wind, hydropower and nuclear energy;
- CO_2 capture and geological disposal.

It is recognised that energy efficiency improvements and reduction of the energy demand alone may not be sufficient to achieve the required reductions in CO_2 emissions. Consequently, international interest in CO_2 capture and disposal has risen rapidly over the last two decades as a potential climate change mitigation strategy with significant potential. In particular, CO_2 emissions from large point sources such as fossil fuel power plants could be captured and disposed of in geological formations, have received great attention.

Another large scale option for low carbon energy supply is the generation of heat and electricity in nuclear power plants. However, the disposal of the generated radioactive waste remains a major concern for society. The necessary separation of radioactive waste from the accessible biosphere through its disposal in adequate geological formations is considered by the nuclear community as the appropriate long term management option and it is being investigated in many countries. The related safety and security requirements are high. So far, the disposal of high level radioactive waste takes place only at the Waste Isolation Pilot Plan (WIPP) in the USA that is a geological repository for permanent disposal of a specific type of waste that is the by-product of the nuclear defence programme. Plans to dispose of long lived intermediate level waste, high level waste and spent nuclear fuel are well advanced in several countries and geological disposal of radioactive waste is likely to start at several sites over the next few decades.

The emplacement of radioactive waste and CO_2 in deep geological formations is considered to be a safe method for isolating these substances from people and from the accessible biosphere.

This report documents the results of the Co-ordinated Research Project (CRP) on Techno-economic Comparison of Ultimate Disposal Facilities for Carbon Dioxide and Radioactive Waste of the International Atomic Energy Agency (IAEA). Research teams from Australia, Bulgaria, Cuba, Czech Republic, Germany, India, Lithuania, Republic of Korea and Switzerland participated in the project.

The main objective of this report is to assist existing and potential interested stakeholders in identifying state of the art information about a range of issues in the geological disposal of CO_2 and radioactive waste relevant for participating countries in a comparative framework. Participants have drawn on results of earlier research in the relevant fields and on the

background material arranged by the IAEA in preparation for the CRP. The investigations focused on the feasibility, options and capacities for geological disposal of CO_2 and radioactive waste prevailing in participating countries to assist policymaking, particularly energy and environmental policies.

A country case study approach was used to conduct a comparative analysis of geological disposal facilities of CO_2 and radioactive waste. The thematic areas assessed include: geology, environmental impacts, risk and safety assessment, monitoring, cost assessment, public perception, and policy, regulation and institutions. The main findings of the study are summarized below:

Geology:

- For CO_2 disposal, sedimentary basins, particularly depleted oil/gas fields, saline aquifers are mostly considered; coal beds may also be suitable;
- For the geological disposal of radioactive waste, a range of sedimentary, igneous and metamorphic host formations are regarded as potentially suitable;
- Potential geological formations have been identified but no final sites have been selected for radioactive waste disposal in countries participating in this CRP;
- Site selection is country specific in both cases.

Environmental impacts:

- For both disposal technologies, environmental impacts are relatively small in comparison to impacts from the rest of the related electricity generation chain;
- Based on assessments from two case study countries (Switzerland and Germany); similar results can be anticipated for other European countries.

Safety and risk assessments:

- In CO_2 disposal, safe performance is based entirely on the host rock and associated injection infrastructure;
- In radioactive waste disposal, safe performance is based on a multibarrier system;
- For radioactive waste disposal, an extensive series of safety standards and guidance are provided by the IAEA. Many Member States have established organisations responsible for the regulation of radioactive waste management, including disposal. Safety assessment methodologies are significantly better established for radioactive waste than for CO_2 disposal.

Monitoring :

- Both radioactive waste and CO_2 disposal have developed particular monitoring technologies tailored to their needs;

- For both radioactive waste and CO_2 disposal, the potential dynamic evolution of the sites is important;
- For radioactive waste disposal monitoring thermal and radiological processes are important whereas for CO_2 disposal the major concern is CO_2 migration.

Cost assessment:

- Lack of data in participating countries makes comparative analysis for both radioactive waste and CO_2 disposal across the countries difficult;
- The costs of both CO_2 and radioactive waste disposal per unit of electricity generated vary significantly across the countries.

Public perception:

- Public perception is better established for radioactive waste disposal compared to CO_2 disposal;
- The public's perception of CO_2 disposal is, in general, low but it is developing rapidly as projects develop;
- In general, there is a lack of systematic analysis and data of possible impacts from information and communication on public perception for both technologies.

Policy, regulation, institutions:

- Policy, regulatory and institutional settings are relatively well defined for radioactive waste disposal and policies are developing rapidly for CCS in some countries, for example in Europe. However, regulations and institutions for CO_2 disposal are undeveloped or underdeveloped in participating countries;
- An extensive set of IAEA Safety Standards and other safety related documents are available about radioactive waste disposal;
- More analysis is required for CO_2 disposal to support its regulation, e.g. to define the legal status of CO_2 as an industrial product vs. waste.

Chapter 1

INTRODUCTION

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1.1. BACKGROUND

Mitigating anthropogenic climate change by the reduction of greenhouse gas (GHG) emissions is an important prerequisite for sustainable development. The ultimate goal of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilize the atmospheric concentration of GHGs at a level that would prevent dangerous anthropogenic interference with the climate system. The Copenhagen Accord of the UNFCCC defines this level at 2°C increase in the global mean annual surface temperature above the preindustrial level [1.1].

The third session of the Conference of the Parties (COP 3) to the UNFCCC adopted the Kyoto Protocol. It is the first legally binding agreement to implement the Convention, but in its original form it had limited participation of major GHG emitters and covered only the period 2008–2012 for GHG reductions by the participating countries. The 18th session of the Conference of the Parties and the 8th session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (COP 18/CMP 8) in 2012 adopted the Doha Amendment to the Kyoto Protocol [1.2]. This includes new commitments in the second commitment period for Annex I Parties who agreed to reduce GHG emissions by at least 18% below 1990 levels between 1 January 2013 and 31 December 2020.

Parties to the UNFCCC established the Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) at COP 17 in December 2011 and launched a "process to develop a protocol, another legal instrument or an agreed outcome with legal force under the Convention applicable to all Parties" [1.3] for approval at COP 21 in 2015 and to enter into force in 2020. The mitigation component of the post-2020 agreement would need to include fast reduction of GHG emissions to achieve the target set in the Copenhagen Accord.

As the major source of GHG emissions, the energy sector will be increasingly affected by the future international climate protection regimes. To meet the increasing energy needs of the world in the 21st century, all energy sources will be required. Depending on the national/regional circumstances, renewable energy sources and nuclear power are projected to contribute at much larger scales than today as the world community moves towards low carbon sources of energy. Fossil fuels are also anticipated to play an important role in the foreseeable future. However, they will need to become environmentally benign by developing and deploying at commercial scales pollutant removal technologies, including CO_2 capture and disposal (CCD). This technology involves the removal of CO_2 before or after the combustion process and its disposal in underground formations, such as aquifers or depleted oil and gas fields. CCD allows reducing CO_2 emissions from burning fossil fuels, in particular coal, considerably. The removed material will have to be disposed of in an environmentally safe manner. Establishing ultimate disposal facilities for the captured CO_2 in suitable geological formations will pose a major challenge.

Another large scale energy option with low CO_2 emissions is nuclear power. The radioactive waste from nuclear power plant operation is also planned to be disposed of in deep geological formations, such as salt domes, clay or granite. Recent discussions about national energy strategies in many Member States of the International Atomic Energy Agency (IAEA) have raised the increasing role of nuclear power in enhancing energy security and mitigating climate change, together with concerns over disposal of radioactive waste. In the case of radioactive waste, principles and practices for safe geological disposal are emerging, but full implementation still remains a challenge as well.

The simultaneously increasing interest in the geological disposal of CO_2 and radioactive waste has brought up a range of questions and opportunities in techno-economic assessments. Following a few sporadic efforts dealing with selected topics, the first systematic comparative assessment concerning the issues involved in the geological disposal of CO_2 and radioactive waste was organized and published by the IAEA [1.4]. It triggered considerable interest in IAEA Member States. In response to this interest, the IAEA initiated the Coordinated Research Project (CRP) on Techno-economic Comparison of Ultimate Disposal Facilities for CO_2 and Radioactive Waste to address these issues further. This report presents the outcome of the CRP.

1.2. TERMINOLOGY

It is important to recognize right at the outset that there are some significant differences of terminology between the management of radioactive waste, and CO_2 capture and disposal. For radioactive wastes, there is a clear distinction between 'storage' and 'disposal' as defined in the IAEA Glossary [1.5]. Storage is defined as: "The holding of spent fuel or of radioactive waste in a facility that provides for its containment, with the intention of retrieval. Storage is by definition an interim measure." Disposal is defined as: "Emplacement of waste in an appropriate facility without the intention of retrieval."

In contrast, the widely used terminology for the waste management of CO_2 is to refer to 'storage' even though there is no intent to retrieve the CO_2 once it has been injected into the ground. If it was radioactive waste, this same process would be referred to as 'disposal'. The emplacement of CO_2 in geological formations is widely called storage, sequestration or disposal. In this report the term CO_2 disposal is mostly used but the three terms are used interchangeably across the chapters. Accordingly, 'disposal capacity' and 'storage capacity' are also used when referring to the ability of a geological formation to take up an estimated volume of CO_2.

Carbon dioxide will be disposed of in deep geological formations using injection boreholes which will then be permanently sealed. In contrast, there are several ways of disposing of radioactive wastes depending on the classification of the wastes. The options include a range of near surface facilities for low level waste (LLW) and short lived intermediate level waste SL ILW). The more radioactive wastes including long lived intermediate level waste (LL ILW), high level waste (HLW), and spent fuel (SF), are typically intended for disposal in geological repositories constructed at several hundred of meters depth below ground surface. The report consistently refers to 'radioactive waste' in preference to the sometimes used alternative of 'nuclear waste'. 'Radioactive waste' is the terminology included in the IAEA Glossary [1.5].

Throughout this report, in comparing and contrasting CO_2 disposal with radioactive waste disposal, only geological disposal – and not storage – of radioactive wastes is taken into consideration. It is noted that the descriptions in the report of radioactive waste disposal in some of the participating countries indicate that they are planning to adopt near surface disposal for their particular waste inventories. These planned near surface disposal facilities have not been included in the in-depth comparisons with CO_2 disposal, but are mentioned as appropriate.

1.3. OBJECTIVES AND SCOPE OF THE CRP

As part of the Agency's ongoing work on sustainable energy development, this CRP was part of the Project on Techno-economic Analysis, under the Sub-Programme Energy Economy Environment (3E) Analysis. The objectives of this Sub-Programme include improving decision making among Member States and international organizations about technology choices and sustainable development strategies. The CRP provided a good platform to share new and important information across Member States through its contribution to international research, and hence in achieving the objectives of the 3E Analysis Sub-Programme. The CRP also helped in creating a link between the nuclear and fossil energy communities.

The major objective of the CRP was to review the state of the art in various aspects of the geological disposal of CO_2 and radioactive waste focusing on features and issues of particular relevance to the participating Member States; to prepare in depth comparative assessments of the similarities and differences relevant for the country or selected regions; to identify the already resolved issues and the remaining key challenges; and to evaluate the policy implications emerging from the comparative study. Participants drew on results of earlier research and specific case studies in the relevant fields and on the background material arranged by the IAEA in preparation for this CRP [1.4]. The investigations focused on the feasibility, options and capacities for disposing of CO_2 and radioactive waste with a view to geological conditions, potential environmental impacts and socioeconomic circumstances (costs and benefits, legal issues, public acceptance, etc.) prevailing in the participating countries or selected regions thereof.

The main reason for selecting the thematic areas of geology, environmental impacts, risk/safety assessment, monitoring, costs assessment, public acceptance, and policy, regulation and institutions was that these were the most relevant themes for the analysis of CO_2 and radioactive waste disposal in deep geological formations. Geology is fundamental to the whole analysis because it is critical to assess the geological formation of the proposed sites in order to understand their properties and suitability to receive and safety contain the wastes. The possible environmental impacts resulting from the disposal of radioactive waste and CO_2 in geological formations are imperative because both waste types can lead to potential burden on the environment and proper measures are required to control the environmental impacts. Any geological disposal facility has to meet the prescribed safety requirements and this necessitates thorough risk and safety assessments. Reliable and cost effective monitoring plays a particularly important role in designing and operating geological disposal facilities. Cost and economic performance estimates are critical in energy and environmental policymaking and it is vital to ensure that the geological disposal facility is financially viable and cost effective. This calls for estimations of the main cost components of the planned repository. Another crucial issue in implementing geological disposal projects is social perception and acceptance. Finally, policy, regulatory and institutional settings are important for implementing geological disposal programmes according to prevailing and newly established rules.

This CRP involved interactions between geoscientists, engineers, economists, safety analysts, and experts in politics and public acceptance representing the nuclear and CCD communities of the participating countries. The study highlighted the actual status and recent developments in these areas and has shown that there are mostly differences, but also many similarities between the two areas. In particular in the areas of environmental impacts, risk and safety assessment, cost estimation and public acceptance, similar approaches and methods are used and the two communities may learn from each other. Increased information exchange between these two communities on a national or even at the international level could be of mutual benefit.

The CRP built on capacity in Member States to analyse the back end of different energy technologies in the context of the climate change problem and to evaluate the potential role of different energy options, including nuclear power. Moreover, the CRP also built new capacity in Member States by supporting comprehensive and systematic national level assessments of various energy and climate protection strategies. National research teams from Australia, Bulgaria, Cuba, Czech Republic, Germany, India, Lithuania, Republic of Korea and Switzerland participated in the CRP. The project was implemented by regular interactions between the national teams. Three Research Coordination Meetings in Vienna were convened and a Consultancy Meeting was hosted by the Research Centre Juelich in Germany. These meetings gave all CRP participants a good opportunity to exchange information regarding the status of their research and to pursue the comparative analysis in the selected thematic areas.

The project created an international network of nine institutions from nine IAEA Member States, representing both developing and developed countries. They continue working together and share knowledge and experience in their respective areas on a bilateral or multilateral basis.

1.4. SCOPE AND STRUCTURE OF THE REPORT

This report is based on deliverables of the CRP participants. The main findings, conclusions and recommendations of the report were elaborated at the final Research Coordination Meeting in Vienna in September 2011 and later revised and updated in the review and revision process. The thematic chapters 2–9 were prepared and coordinated by the respective lead authors. The complete report was reviewed by all participants and two external reviewers: a radioactive waste disposal and a CO_2 disposal expert.

This report about the geological disposal of two waste products related to electricity generation highlights the new knowledge that has emerged from the comparative assessments in the selected thematic areas (geology, environmental impacts, risk/safety assessment; monitoring; costs assessment; public perception; and policy, regulation and institutions). It provides guidance for those who plan to undertake similar studies for exploring disposal options for CO_2 and radioactive waste in a given country for supporting national energy policy, or for one of the waste products across several countries to provide information for possible regional collaborative strategies. Up to now such reviews have been mostly carried out separately by the two communities for their respective waste.

The objective of this report is to document the outcome of the coordinated research conducted within the CRP. The core of the report comprises the thematic chapters selected in the frame of the CRP to conduct a comparative analysis of CO_2 and radioactive waste disposal.

Results of the CRP reported here are expected to assist existing and potentially interested stakeholders in identifying state of the art information about a range of issues in the geological disposal of CO_2 and radioactive waste. The investigations of the feasibility, options and capacities prevailing in the participating countries will assist policymaking, particularly in energy and environmental policy.

The results of this CRP, as documented in this report, indicate that there are a number of similarities between these two options and that the two communities may learn from each other. The results also show that useful and valuable information can be derived even from the differences.

The report is intended for a variety of stakeholders. It is hoped to contribute to framing energy strategies and policies at the government level in Member States struggling with the dilemma between nuclear energy entailing radioactive waste disposal or fossil fuels requiring CO_2 disposal. Other audiences include research organizations, policy analysts, policy advisors, regulators and utility operators in Members States.

Following this introduction (Chapter 1) about the background, objectives and scope of this report, Chapter 2 focuses on the geological aspects of CO_2 and radioactive waste disposal. Chapter 3 provides an overview of environmental impacts by employing the life cycle assessment (LCA) methodology. The environmental burdens and impacts from radioactive waste and CO_2 disposal are assessed in the context of the complete energy chain for generating electricity from fossil and nuclear power plants. Chapter 4 discusses risk and safety assessments for the disposal concepts, exposure definition, limits for safety/risk evaluation, methodologies available and results achieved from the evaluation of certain scenarios. Chapter 5 focuses on monitoring in both disposal concepts, before, during and after their operation. Chapter 6 discusses disposal costs by analysing the estimated costs of geological disposal of CO_2 and radioactive waste. A comparative analysis of CO_2 and radioactive waste disposal costs is performed, specific and total costs are calculated for selected countries. Chapter 7 examines the similarities and differences in public perception and public acceptance between CO_2 and radioactive waste disposal. Chapter 8 presents a comprehensive analysis of the policy, regulation and institutional issues in several participating and other major countries in a comparative framework.

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Chapter 2

GEOLOGY

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2.1. INTRODUCTION

This chapter presents an overview of the geological issues involved in the ultimate disposal of carbon dioxide (CO_2) and radioactive waste in geological formations. It is based on the information collected by research teams participating in this Coordinated Research Project (CRP) in their own Member States. The chapter is intended to serve as a reference for the thematic discussions in subsequent chapters.

The main objectives of the chapter are:

- To present an up to date overview of the methods in geological assessments for the disposal of CO_2 and radioactive waste;

- To review the specific geological conditions and the status of research in the countries involved in this CRP;

- To present a comparative analyses of the geological issues in the disposal of CO_2 and radioactive waste.

The countries involved in the geological component of this CRP include Bulgaria, Cuba, the Czech Republic, Germany, India, the Republic of Korea and Switzerland.

2.2. DISPOSAL METHODS

This chapter presents a general overview of the methods to dispose of CO_2 and radioactive waste.

2.2.1. CO_2 disposal

2.2.1.1. Geological disposal options

There are several options for the geological disposal of CO_2 (see Fig. 2.1):

- Depleted natural oil and gas fields;
- Deep saline aquifers (water saturated reservoir rocks);
- Deep unmineable coal seems;
- Use of CO_2 in enhanced oil recovery;
- Use of CO_2 in enhanced coal bed methane recovery;
- Basalts, oil shales and cavities.

So far, mostly the first three options have been considered in the countries participating in this CRP.

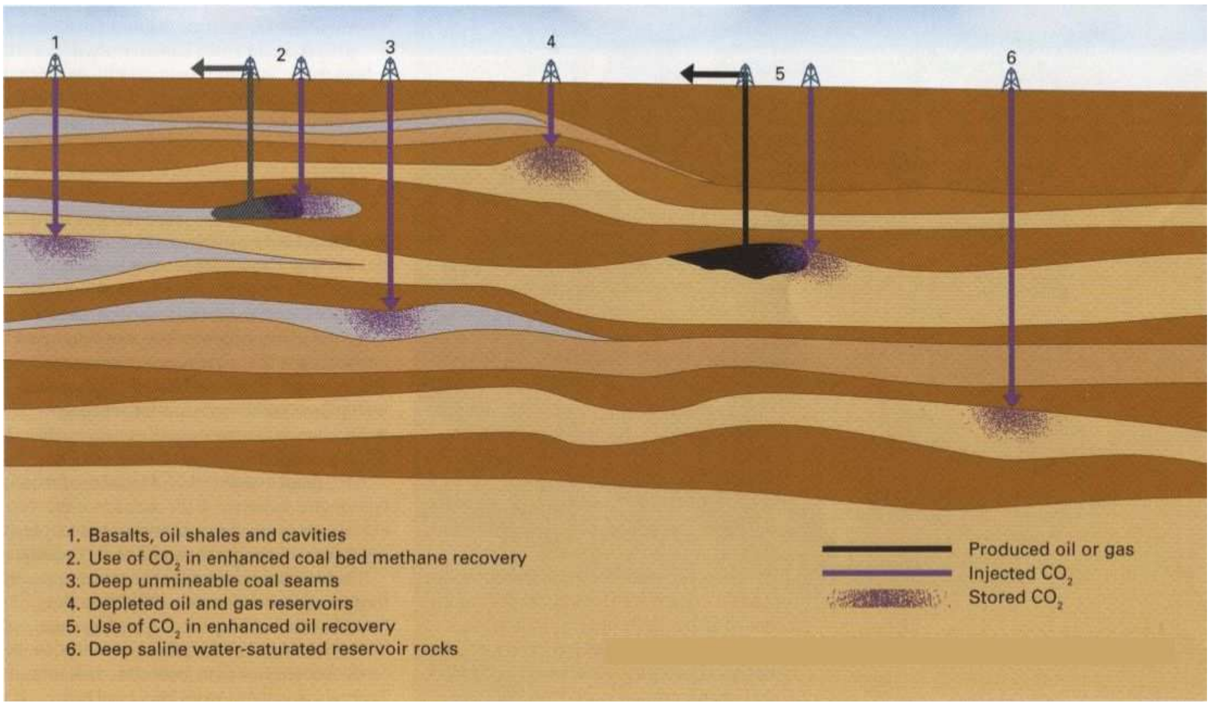

FIG. 2.1. Geological disposal options for CO2. Source: based on [2.1]

Disposal in depleted oil and natural gas fields

CO_2 disposal in depleted natural oil and gas fields offers numerous advantages, the most significant of which is that the caprock is impermeable and its characteristics are well known. Indeed, natural reservoirs have proven their capacity to contain hydrocarbons for many millions of years. Moreover, CO_2 disposal of this type is a practice well known to the oil and gas industry. CO_2 is injected into oil fields to reduce crude viscosity and enhance mobility, thereby improving the recovery rate. This technique is known as enhanced oil recovery (EOR). A part of the infrastructure already in place for the exploration and production of crude oil (such as piles and wells) can be reused for CO_2 disposal operations, thereby helping to control costs.

However, reservoirs are not always located near the sources of CO_2 production, nor are the available disposal capacities always sufficient to meet all needs.

Disposal in saline aquifers

There are numerous aquifers located in sedimentary basins, with areas of up to several thousand km^2. They can be either offshore or onshore. Formed on porous, permeable rock often saturated with brackish water or brine which cannot be used as drinking water, these aquifers are potential disposal sites for considerable quantities of CO_2, provided they are at a sufficient depth (>800 m) and have overlying impermeable layers.

Although this type offers a large disposal potential, extensive work is still needed to gain better knowledge of these aquifers.

Disposal in unmineable coal beds

In this option, the coal bed is not used as a reservoir, but it stores the CO_2 by absorption of the gas. Provided the coal bed is adequately covered by an impermeable caprock, this technique would also allow for enhanced coal bed methane recovery (ECBMR).

However, the present understanding of this disposal type is still incomplete. It is an option for the future, if the problem of how to inject large volumes of CO_2 into low permeable coal is solved.

Inside the layer of porous rock, there are three natural trapping processes, which increase the safety of CO_2 disposal over time. These are residual, dissolution and mineral trapping.

- *Residual trapping:* some of the injected CO_2 is trapped in the tiny pores of the rocks and cannot move, even under pressure;
- *Dissolution trapping:* a portion of the injected CO_2 dissolves into the surrounding water;
- *Mineral trapping:* over time, some of the heavy CO_2 rich water sinks to the bottom of the reservoir, where it may react to form minerals such as those found in limestone or sandstone.

2.2.1.2. Basic criteria for site selection

For a site to be suitable for CO_2 disposal, some basic geological criteria have to be fulfilled. They include:

- Sufficient *depth of reservoir* to ensure that CO_2 reaches its supercritical dense phase, but not so deep that permeability and porosity becomes too low;

- Effective *petrophysical reservoir properties* to ensure that CO_2 injectivity is economically viable and that sufficient CO_2 can be stored;

- *Integrity of natural seals* to hinder CO_2 release;

- Sufficient *disposal capacity* to retain the amount of CO_2 expected to be released from the source. This will determine the economic performance and the potential exploitation of the resource.

Depth of reservoir: The density of CO_2 rich gases increases with depth as a result of increasing temperature and pressure. Under normal reservoir conditions, there is a steep increase in the density with an associated decrease in the volume of CO_2 at depths between 600–800 m (Fig. 2.2). This is dependent on the geothermal conditions and pressure of the formation in question. At depths of more than 800 m (~8 MPa pressure), the CO_2 will be in its dense (liquid or supercritical) phase; at depths less than this, it will be in its gas phase and not dense enough for disposal to be economically viable. For this reason, disposal is recommended in formations that lie at depths of 800 m or deeper.

However, with increasing depth, the permeability and porosity of the sandstone reservoir normally decrease, due to digenetic alterations. This has a negative effect on the disposal capacity of the reservoir and the ability to inject CO_2 into the reservoir as described below under petrophysical reservoir properties. For this reason, it is recommended, as a rule of thumb, that the disposal depth is not greater than 2500 m, unless sufficient data are available to validate acceptable porosity and permeability values at a greater depth [2.2].

Petrophysical reservoir properties: A reservoir must have some basal petrophysical properties to be suitable for CO_2 disposal. Here, the basic parameters are the permeability and the porosity. High permeability values ensure that it is easy to inject CO_2 into the reservoir and high porosity values ensure that there is pore space available for the CO_2 disposal.

- *Permeability* is a measure of the ability of a material to transmit fluids. In the case of CO_2 disposal, the material is typically a rock of sedimentary origin. The permeability is of great importance in determining the flow characteristics of the injected CO_2 in the reservoir. Permeability is commonly symbolized as κ, or k. The unit used for describing permeability is millidarcy (mD) (1 Darcy = 10^{-12} m^2). The permeability needs to be measured either directly (using Darcy's law) or through estimation using empirically derived formulas. As a general rule, the formation permeability must exceed 200 mD for a specific reservoir to provide sufficient injectivity [2.3]. However, values greater than 300 mD are preferred.

- *Porosity* is a measure of the relative volume of void space in a rock to the total rock volume. The void may contain, for example, water or hydrocarbons (gas and oil). Porosity is measured in percent, between 0 and 100%. Effective porosity (also called open porosity) refers to the fraction of the total volume in which fluid flow is effectively taking place (this excludes dead end pores or non-connected cavities). These spaces or pores are in the juvenile state of water bearing where oil and gas accumulate in hydrocarbon deposits. Therefore, a high effective porosity increases the amount of CO_2 that can be stored. The fraction (by volume) of a reservoir's pore space that can be filled by CO_2 (in free or dissolved form) is called the disposal efficiency. In the case of natural gas disposal in aquifers, a bulk gas saturation of more than 50 volumetric percent may be reached. For trap structures, the ability to displace pore fluids from within the trap t*o surrounding reservoir rocks will govern the value of the disposal efficiency. As a general* rule, porosity should be larger than 20% [2.2]. Porosity below 10% is restraining.

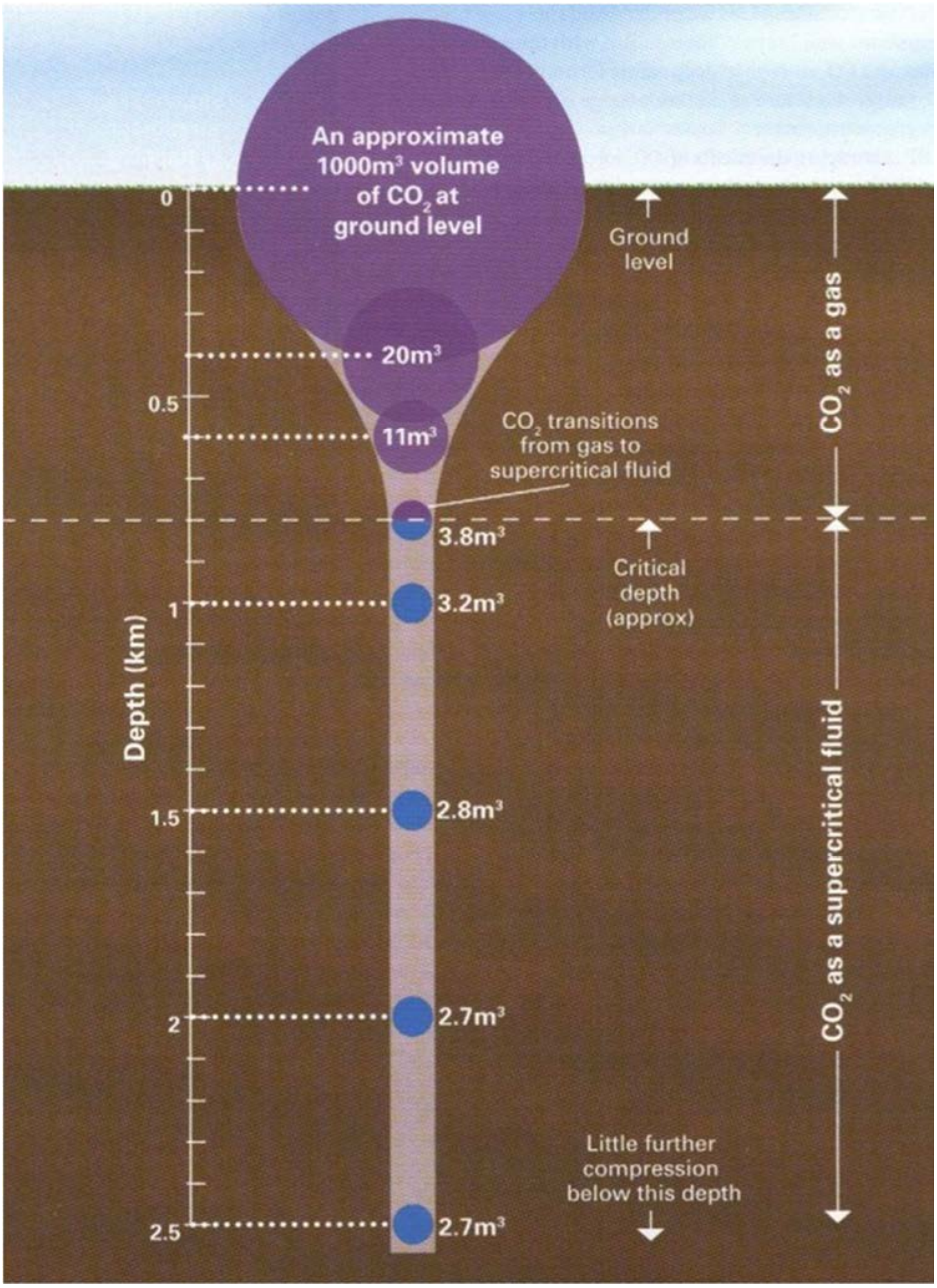

FIG. 2.2. CO_2 volume reduction with depth. Source: based on [2.1]

Integrity of the natural seal/caprock: Given the buoyant nature of CO_2, a reservoir must have an overlying seal/caprock to be able to store CO_2 effectively. Typical formations with good sealing properties are rocks with low permeability values, such as lacustrine and marine mudstones, evaporates and dense carbonates. The integrity of the seal is governed by the thickness of the sealing formation, the absence of faults crossing the formation, as well as the impact of geochemical interactions between the CO_2 and the caprock. Parameters that have influence on the properties of a rock as a seal are the following:

- *Permeability:* in the case of a seal, the permeability should be as low as possible, thereby hindering the transport of CO_2 through the matrix of the caprock;

- *Seal thickness:* a thick seal naturally has a positive effect in hindering the leakage of CO_2 through the seal. A thickness less than 20 m is deterrent, whereas thickness greater than 100 m is preferable [2.2];

- *Faults:* they may have several, partially opposing effects on the migration of CO_2. Sealing faults can constitute traps, thereby both trapping CO_2 and constraining its migration pathways. Non-sealing faults, in contrast, may enable CO_2 to escape through the seal along faults and, thereby, potentially escape to the atmosphere or the sea. Seal integrity may also be compromised by hydrofracturing the caprock, which occurs when the pore pressure of the reservoir is the same as the least principal stress in the overlying unit [2.4];

- *Tectonic activity:* to avoid a sudden escape of pressurized CO_2 along faults, disposal sites should not be in an area of recent seismic or tectonic activities. Pressurized CO_2 ascending along faults could expand rapidly at subcritical conditions, reducing the fault strength and opening up pathways for the gas to escape to the surface. The injection of large quantities of CO_2 may also change the local stress field, and thus trigger seismicity. Therefore, statistics on seismic activities should be checked for potential disposal sites;

- *Heterogeneity of the seal:* a homogeneous, low permeable seal inhibits the migration of CO_2 through the seal. Abundant inhomogeneities, such as sandstone beds and lenses in a seal of mudstone, increase the risk of CO_2 leakage, as sandstone occurrences may be connected directly or by small faults, thereby forming migration pathways for the CO_2;

- *Geochemical interactions:* once CO_2 dissolves into water, it forms carbonic acid. This will acidify the formation water and potentially attack and alter the caprock and fractures within the caprock. These chemical interactions might change the physical characteristics of parts of the seal and thus potentially enhance CO_2 migration towards the surface.

Disposal capacity: All identified disposal sites should be capable of storing the lifetime emissions of the selected source point(s). With respect to power plants, nominal plant lifetimes are approximately 20–30 years. If a coal fired power plant, as an example, has an annual CO_2 emission of 4 million t (Mt), then the disposal site should, consequently, have a minimum capacity of 80 Mt. Lifetimes will vary according to different types of industry. As a general rule of thumb, the total disposal capacity of a reservoir should be much larger than the total amount of CO_2 from the source.

Geological parameters that influence the disposal capacity include: trap type, occurrence of faults, heterogeneity of the reservoir, thickness and areal extent of the reservoir. In addition, the petrophysical properties of the reservoir naturally have a large effect on the disposal capacity.

- *Trap type:* CO_2 disposal capacity depends not only on the properties of the reservoir itself, but also on the nature of its boundaries. As described in Chadwick et al. [2.2], very little CO_2 can be injected into the water filled porosity of a small reservoir with perfectly sealed non-elastic boundaries, as the only space available will be that created by the compression of the water and rock. Furthermore, this may result in an unacceptable rise in reservoir pressure towards the seal, implying that CO_2 may leak through the seal along microfractures or faults or migrate through the matrix of the seal if the pressure overrides the capillary entry pressure of the seal.

  For efficient disposal, it is therefore necessary that a significant proportion of the native pore fluid is displaced from the reservoir over the injection period. This may occur either by anthropogenic production of fluids (oil and gas), by deliberate production of formation water or by displacement of the formation water to the aquifer outside the closure by the injected CO_2.

  Aquifers in which formation water is expelled by the injected CO_2 may be divided into *trapped aquifers and open aquifers.*

  - *Trapped aquifers:* the majority of suitable structures that can keep CO_2 over long periods of time consist of some sort of three dimensional structural closures that form different types of traps. The ideal convex structure is the isolated dome that dips in all directions away from the central high;

  Eventually, all kinds of different shapes of those closures will occur in nature, from circular to elongated to complex. A common characteristic is, however, that they will be terminated upwards by a highest point that can be measured directly (wells) or indirectly (seismic profiles) as depth to the crest of the structure. In the case of complex shaped closures, several crests may be present. Large structures naturally favour the disposal capacity compared to minor structures;

  - *Open aquifers*: CO_2 disposal may also take place in open, dipping aquifers [2.2]. The seals above these aquifers are dipping and may be incomplete; they would inhibit direct vertical migration of the injected CO_2 and deflect the migration path to or near horizontal course, but they would not hold the CO_2 permanently in situ. Ultimately, the CO_2 would likely reach a non-sealed part of the reservoir and escape into the atmosphere or the ocean if it were not kept within the reservoir by counteracting processes. Suitable counteracting processes that have an effect at relevant timescales (hundreds to thousands of years) are the dissolution into formation water and residual gas trapping due to relatively permeability hysteresis. Open dipping aquifers may, therefore, provide effective CO_2 disposal options if the above mentioned processes operate and there is an adequate distance between the injection well and the leakage point.

- *Heterogeneity and faults:* internal barriers within the reservoir, such as faults or lithological inhomogeneities, need to be considered, as these may divide the reservoir into separate unconnected or poorly connected compartments that may behave independently of each other. Therefore, it is easier to estimate the CO_2 disposal capacity for non-faulted reservoirs with a homogeneous lithology, compared to reservoirs, which are heavily faulted and are strongly heterogeneous. Furthermore, in the latter type of reservoirs, the injection of CO_2 may require at least one well per compartment [2.5] and the dispersal pattern of the injected CO_2 is more difficult to predict. On the other hand, lithological heterogeneity may promote additional fixing processes of CO_2 within the reservoir in addition to the structural trapping. Intra-reservoir heterogeneity is, therefore, likely to increase effective disposal capacity in the longer term by encouraging dissolution of CO_2 into the formation water, promoting 'strati graphical' trapping of CO_2 as an immobile residual phase and promoting geochemical reaction leading to chemical 'fixing' [2.2].

- *Thickness and areal extent*: the size of the CO_2 disposal structure will be defined by the last closing contour at a certain depth. Below that depth, the CO_2 will not be contained within the structure and be allowed to spread uncontrollable. The areal extent of a CO_2 disposal site will have an impact on the surface area, the so called 'footprint', which will have to be included in further investigations once a disposal site is planned.

  Reservoirs of less than 20 m of cumulative thickness of good reservoir sandstone beds are thought not to be suitable for the disposal of large amounts of CO_2 [2.2]. As a rule of thumb, the thickness should be larger than 50 m. Naturally, a small thickness can be compensated by a large areal extent of the reservoir. This, however, also implies a large 'footprint' area, making eventual monitoring of CO_2 leakage to the surface more complicated and expensive.

  In addition, it requires a large area to be mapped in detail to identify potential leakage pathways (particularly faults). Information on the probable areal extent of a 'footprint' can be estimated with the help of depth structure maps and seismic profiles, which can help to define the extent of the structure in more detail, as well as for the occurrence of possible faults.

- *Other parameters with implication on the disposal capacity:* apart from the above mentioned parameters, the CO_2 volumes that can be stored in aquifers depend on many commonly poorly determined parameters and issues as described in [2.2], including:

  - Residual saturation trapping, in which capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix immobilize a proportion of the injected CO_2;

  - Geochemical trapping, in which dissolved CO_2 reacts with the native pore fluid and the minerals making up the rock matrix of the reservoir [2.6]. CO_2 is incorporated into the reaction products as solid carbonate minerals and aqueous complexes dissolved in the formation water;

  - The amount of CO_2 that will dissolve into the saline pore fluids.

2.2.1.3. Disposal capacity standards

Disposal capacity assessment begins with identifying sedimentary basins. Once the suitable sedimentary basins have been outlined, the next step is to identify potential reservoir and sealing units for CO_2 disposal and characterization of their geological and physical properties. At this point, regional CO_2 disposal estimates based on the bulk volume of aquifers can be calculated.

More precise estimates can be provided if stratigraphic or structural traps with suitable reservoir and sealing properties are identified within the aquifers and the disposal potential of the individual trap is calculated. Regional estimates can be calculated as the sum of the disposal potential of all traps.

The disposal capacity estimates are generally regional estimates based on the bulk volume of a deep saline aquifer or site specific estimates. In both cases, a disposal efficiency factor is included in the calculation. Theoretical disposal capacities without any disposal efficiency factor applied are unrealistic, useless and only lead to misunderstandings.

The disposal efficiency factor is the ratio of used space over available space either considering a trap structure or a regional aquifer. The effective regional disposal capacity estimates are based on the bulk volume of aquifers and the application of a disposal efficiency factor as a supplement to regional estimates, based on the sum of capacities in individually identified traps[1].

2.2.2. Radioactive waste disposal

2.2.2.1. Geological disposal

This section draws on studies of Witherspoon and Bodvarsson [2.7] and [2.8], Witherspoon [2.9], Chapman [2.10] and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) [2.11] to present up to date information on deep geological repositories.

Geological disposal of high level radioactive waste (HLW) is now the accepted disposal solution worldwide. A range of host geological formations has been considered for deep repositories, including hard crystalline rocks (granite, gneiss and volcanic tuff), argillaceous rocks (clays, mudrocks, shales) and evaporate formations (dome and bedded salts).

Disposal in a rock formation is the most likely solution for HLW. Geological disposal refers to the disposal of solid radioactive waste in a facility located underground in a stable geological formation (usually several hundred meters or more below the surface) that provides long term isolation of the radionuclides in the waste from the accessible biosphere. The Safety Guide published by the IAEA [2.12] specifies the factors to be taken into account in national site selection programmes.

The geological environment is expected to contribute to ensuring safe disposal in three ways:

- Providing physical isolation of the waste from the near surface environment and the potentially disruptive processes that occur there;
- Maintaining a geochemical, hydrogeological and geomechanical environment that is favourable to the preservation and performance of the engineered barrier system;
- Acting as a natural barrier to restrict the access of water to the waste and the migration of active radionuclides.

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[1] The formulas for the estimation of the capacity in hydrocarbon fields, deep saline aquifers and coal fields are given in the Appendix to this section.

The siting of such a disposal facility is a multistage process. The following factors need to be considered when a site is being selected: geological setting, possible future natural changes, hydrogeology, geochemistry, events resulting from human activities, construction and engineering conditions, transportation of waste, protection of the environment, land use and social impacts.

Many countries have screened their territories for suitable geological sites for geological disposal facilities for HLW. The countries' site selection programmes consist of four stages: conceptual and planning, area survey, site characterization and site confirmation.

2.2.2.2. Disposal technology

Deep geological disposal (at hundreds of metres' depth) is the option favoured internationally for the long term management of heat generating radioactive wastes, such as spent fuel (SF) and HLW, and radioactive wastes with considerable content of long lived radionuclides, such as long lived intermediate level waste (ILW) that produces only negligible amounts of heat [2.3].

Direct experience with geological disposal of HLW does not yet exist on a large scale, as there is only one operating repository, the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA. Several countries' disposal programmes for SF and HLW are, however, nearing fruition (Finland, Sweden and France). Extensive programmes of site characterization from the surface and from underground have been carried out, and considerable experience has been gained in carrying our safety assessments, developing safety cases, research and development, and the development of engineering designs for geological disposal. There are also well developed regulatory systems in place for evaluating the proposals for implementing geological disposal.

The fundamental principles involved in geological disposal are discussed in Chapman and McKinley [2.13], Savage [2.14], Chapman and McCombie [2.15] and Alexander and McKinley [2.16]. A key concept is the multibarrier principle, according to which long term safety is assured by a series of engineered and natural barriers that act in tandem (Fig. 2.3). Geological repositories are designed to make also use of passive safety. These barriers prevent or reduce the transport of radionuclides in groundwater that is generally the most important transport mechanism. The barrier may also influence the migration of gas produced in the repositories by chemical and biochemical reactions and by radioactive decay [2.17].

The multibarrier system (Fig. 2.3) consists of two main elements:

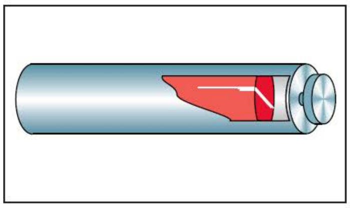
- The engineered barrier system comprising the solid waste matrix and various containers and backfills to immobilize the waste inside the repository;

- The natural barrier (also referred to as the geosphere), which is principally the rock and groundwater system that isolates the repository and the engineered barrier system from the accessible biosphere. The host rock is part of the natural barrier in which the repository is located. In some cases, the host rock is effectively equivalent to the geosphere, e.g. in the situation where the crystalline rock in which the repository is located extends to the surface. In other cases, parts of the geosphere outside the host formation may play an important role in contributing to the natural barriers.

Safety barrier system for HLW

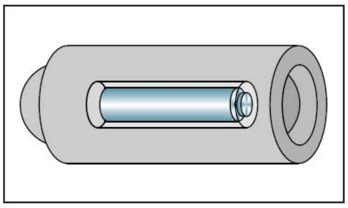
Waste matrix (glass)

- Fixation of radionuclides in the glass matrix
- Low glass corrosion rate



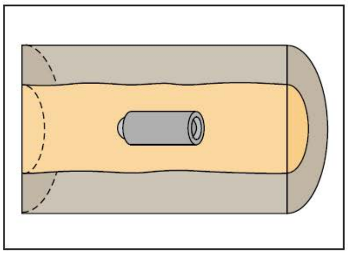
Disposal container

- Containment of the waste for several thousand years
- Thereafter: Restricted water inflow and retention of radionuclides (sorption on corrosion products)



Backfill (bentonite)

- Suitable interface between disposal containers and the host rock
- Favourable radionuclide retention properties
- Favourable conditions for long-term stability of the disposal containers



Host rock

- Low groundwater flux
- Favourable structure of the pore space
- Favourable geochemical conditions for radionuclide retention
- Favourable conditions for long-term stability of the engineered barriers

Geological situation

- Favourable host rock configuration for arrangement of the disposal tunnels
- Favourable conditions for long-term stability of the barrier system
- Absence of raw materials deposits that would be workable in the foreseeable future

Placement of disposal tunnels deep underground

- Isolation of the waste
- Prevention of unwanted access
- Protection from unintentional intrusion
- Protection from erosion

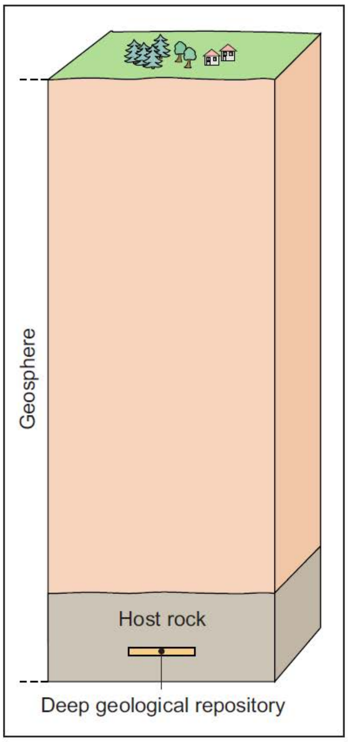


FIG. 2.3. The safety barrier system for HLW. Source: Nagra [2.18].

Reproduced with permission of Nagra, NTB 08-05, fig. 4.3-5, translation by Nagra.

The long term safety of a deep geological repository for radioactive waste will be strongly dependent on the performance of the geosphere. It isolates the radioactive waste from possible future intrusions by humans, provides a stable physical and chemical environment for the engineered barriers within the repository, insulates against external perturbations, such as earthquakes and climate change, and prevents, delays and attenuates radionuclide transport by virtue of its hydraulic and sorptive properties [2.12].

A safety case for a deep geological repository typically makes use of geoscientific information within a long term safety assessment that evaluates the potential impacts of the repository [2.12]. These studies require a conceptual model of the geosphere that quantifies, for instance, groundwater flow rates and consequent radionuclide transport (as, eventually, the radioactive waste will come into contact with the groundwater, although this process may take place after many thousands of years). Geoscientific information can play a larger role in the development of a safety case; in particular, geoscience can offer multiple and independent lines of qualitative and quantitative evidence to support a safety case. Moreover, it can play an important role in other repository activities that bear on safety, such as site selection and repository design.

2.3. COUNTRY CASE STUDIES

2.3.1. Bulgaria

The industrial collapse in Bulgaria after the political changes in 1990 significantly reduced the amount of CO_2 emissions in the subsequent years, far below the limits specified in the Kyoto agreement (Fig. 2.4). The closing of some larger emitters (such as the largest steel plant), the improvement of combustion technologies and the world economic crisis have also reduced industrial CO_2 emissions.

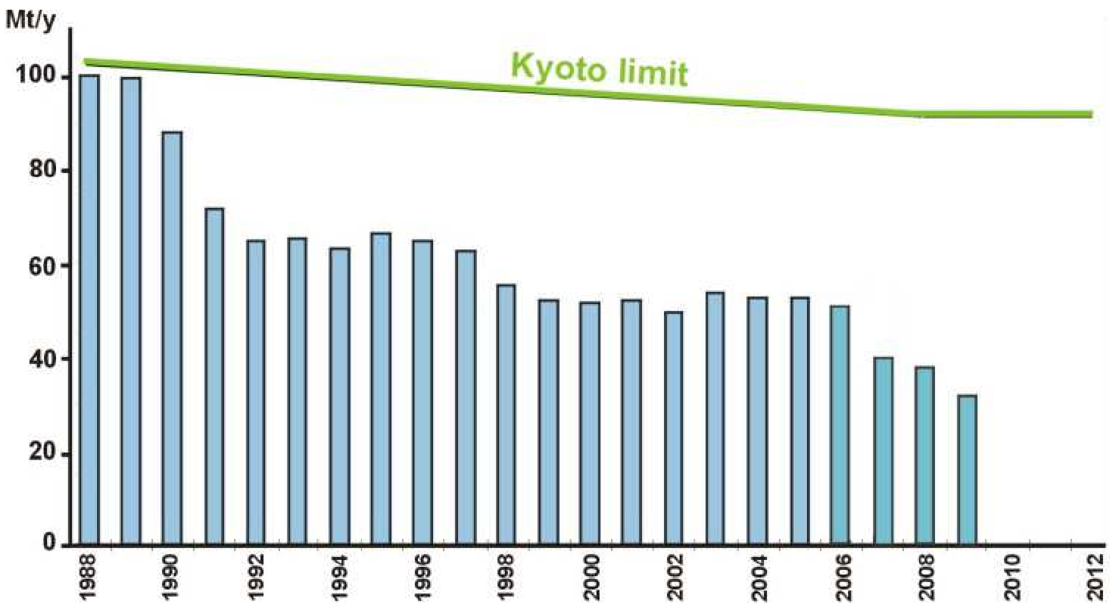


FIG. 2.4. Industrial CO_2 emissions and the limit in the Kyoto Protocol for Bulgaria.

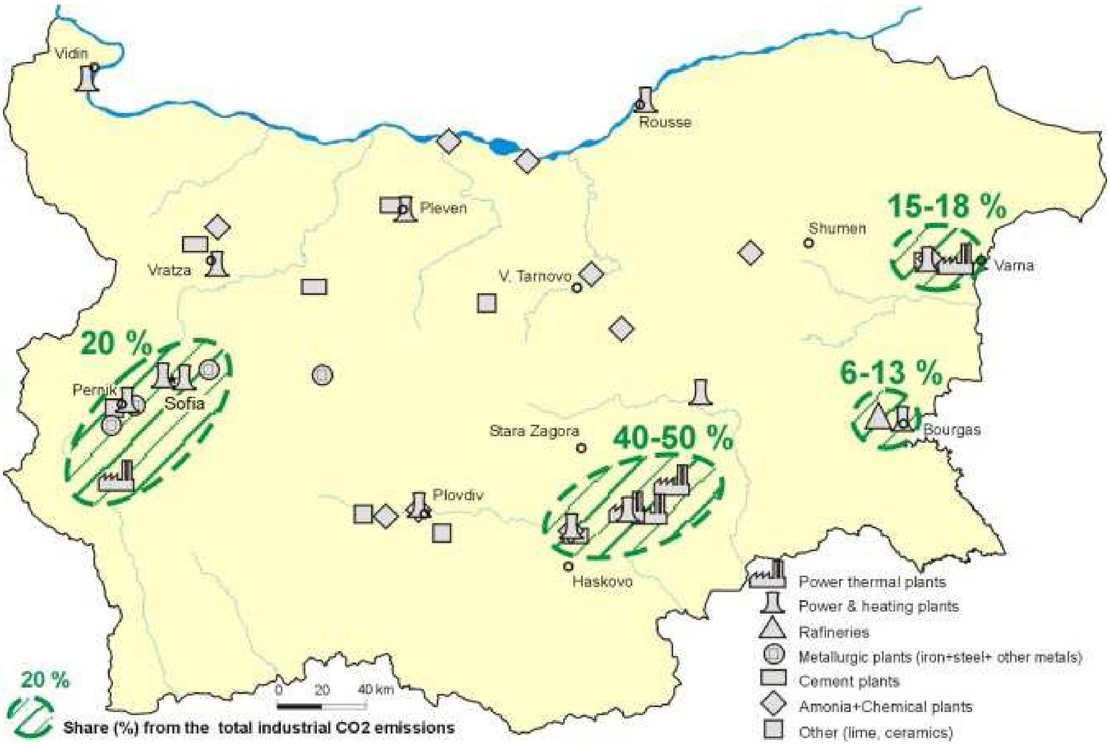


FIG. 2.5. Location of large CO_2 emissions sources in Bulgaria in 2002.

The regional distribution of large CO_2 sources (>0.1 Mt/year) and their industrial type are shown in Fig. 2.5. The largest CO_2 emitters in the country include all thermal power plants, two combined heat and power plants and the Burgas refinery. They produced about three quarters of all industrial CO_2 emissions in 2002. In Bulgaria, there are four zones with a high concentration of industrial CO_2 emissions sources that produced a total of about 85% of the national emissions. They are mostly located in the southern part of the country (see Fig. 2.5).

The Kozloduy NPP, located on the Danube river bank, is the only nuclear plant in operation at present. There are six reactors on the site. The first four units (1 to 4) are WWER-400, V-230 reactors. They were shut down after Bulgaria became a Member State of the European Union. The other two reactors (5 and 6) are WWER, V-320 reactors and are still in operation (see Table 2.1 and Fig. 2.6).

A pool type research reactor (IRT-2000, 2 MW) is operated by the Bulgarian Academy of Science (BAS). It was commissioned in 1961 and, at present, it is out of operation. The construction of a new NPP in Belene started in 1987 but has not been completed yet.

About 90% of the radioactive waste in Bulgaria is from the Kozloduy NPP. The remaining 10% is from radiation sources in medicine, science, industry, agriculture, etc.

There is only one operating repository for low and intermediate level waste (LILW) in Novi Han, which was commissioned in October 1964. The repository covers a 40 hectares site, located at 920 m altitude in the Lozen Mountain, about 30 km from Sofia. Its operation was temporarily suspended by the Bulgarian Nuclear Safety Authority (CUAEPP) in 1994 because of upgrading. The construction of another repository for low level waste (LLW) and intermediate level waste near the Kozloduy NPP was completed in 2011.

TABLE 2.1. THE KOZLODUY NUCLEAR POWER PLANT

Unit	Type	Thermal capacity (MW(th))	Electric capacity (MW(e))	Commissioning date	Lifetime (years)
1	WWER 440/230	1350	440	October 1974	30 (closed)
2	WWER 440/230	1350	440	November 1975	30 (closed)
3	440/230	1350	440	December 1980	30 (closed)
4	WWER 440/230	1350	440	June 1982	30 (closed)
5	WWER 1000/320	3000	1000	November 1987	30
6	WWER 1000/320	3000	1000	May 1989	30

FIG. 2.6. NPPs and radioactive waste repositories in Bulgaria.

2.3.1.1. Geological opportunities for CO_2 and radioactive waste disposal

Bulgaria has an extensively varied and complex geological structure [2.19] and [2.20]. Several major tectonic units are recognized, including the Moesian platform, the Alpine thrust folded belt with Tertiary foredeep (named Kamchija depression), the Sakar and Strandzha orogenic zones and a system of small syn- to post-orogenic Tertiary extensional basins (Fig. 2.7). In addition, the offshore area covers some parts of the Western Black Sea basin.

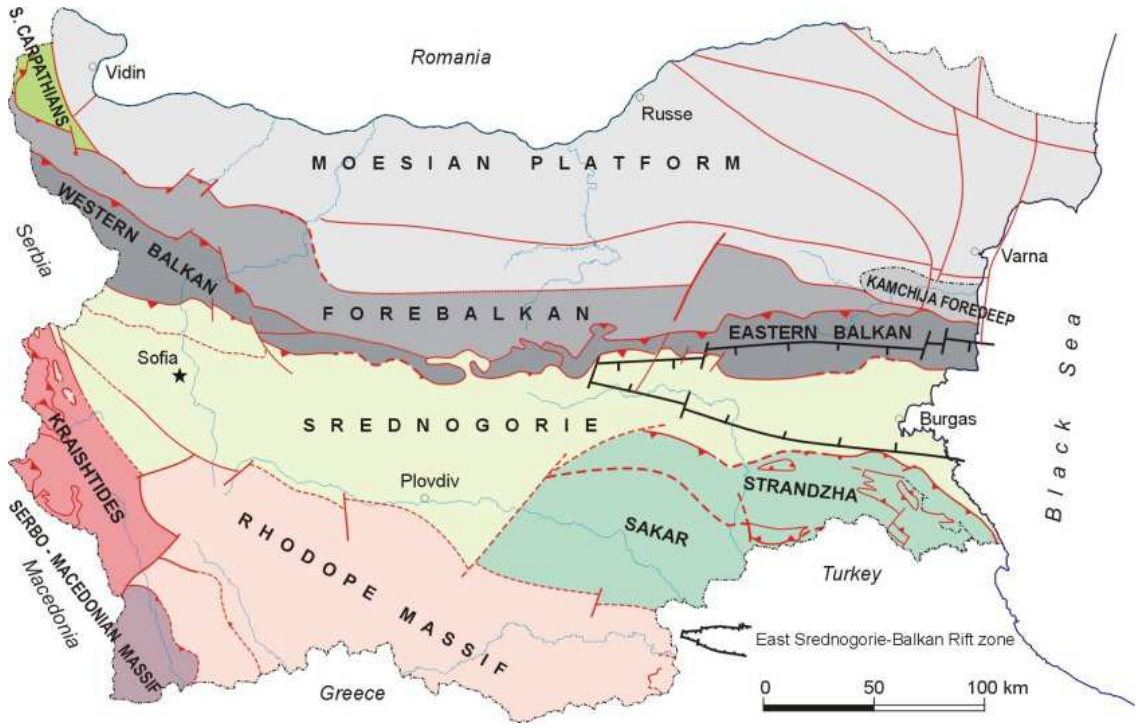


FIG. 2.7. Main tectonic units in Bulgaria. Sources: [2.19] and [2.20].

Two branches of the Alpine orogenic belt and their foreland are located in Bulgaria (Fig. 2.7). *The northern branch*, represented by the Balkanides (Balkan and Forebalkan), crosses the country in the middle from west to east. The Moesian platform is a foreland with a thick Phanerozoic sedimentary succession that is 4–13 km thick. *The southern branch* comprises the Rhodope Massif, Kraishtides and Srednogorie. The main tectonic units and sedimentary basins are described in Georgiev and Dabovski [2.20].

In Northern Bulgaria (Moesian platform and Forebalkan), there is a thick Phanerozoic sedimentary succession, with a thickness of 4–13 km. In southern Bulgaria, the sedimentary spreading is restricted in area and thickness and related with numerous small intra-mountain young basins. Only the Thracian depression is larger, and sedimentary thickness exceeds 1000–1500 m in some parts. The Bulgarian offshore sites have some promising sedimentary features for the local spreading of deep saline aquifers.

CO_2 disposal

The Bulgarian options for CO_2 disposal in geological formations include some of the saline aquifers, depleted gas fields and unmined deep coal beds [2.21].

Saline aquifers offer the biggest CO_2 disposal potential in the country. In the sedimentary successions of different basins and zones, the presence of reservoir strata, horizons or levels with effective seals has mostly local or zonal spreading. The most promising potentials are related to some karstified and fractured carbonate reservoirs in the Devonian and Upper Jurassic-Valanginian, and some coarse grained clastic reservoirs in the Lower Triassic, Middle Jurassic and Middle-Upper Eocene stratigraphic units. Six local zones and two individual structures have been identified as appropriate for CO_2 disposal so far (Fig. 2.8) [2.21]. They are related to the Devonian, Lower Triassic, Middle Jurassic, Upper Jurassic-

Valanginian and Middle-Upper Eocene reservoirs. Four of the selected aquifers are located in northern Bulgaria, the other two in southern Bulgaria.

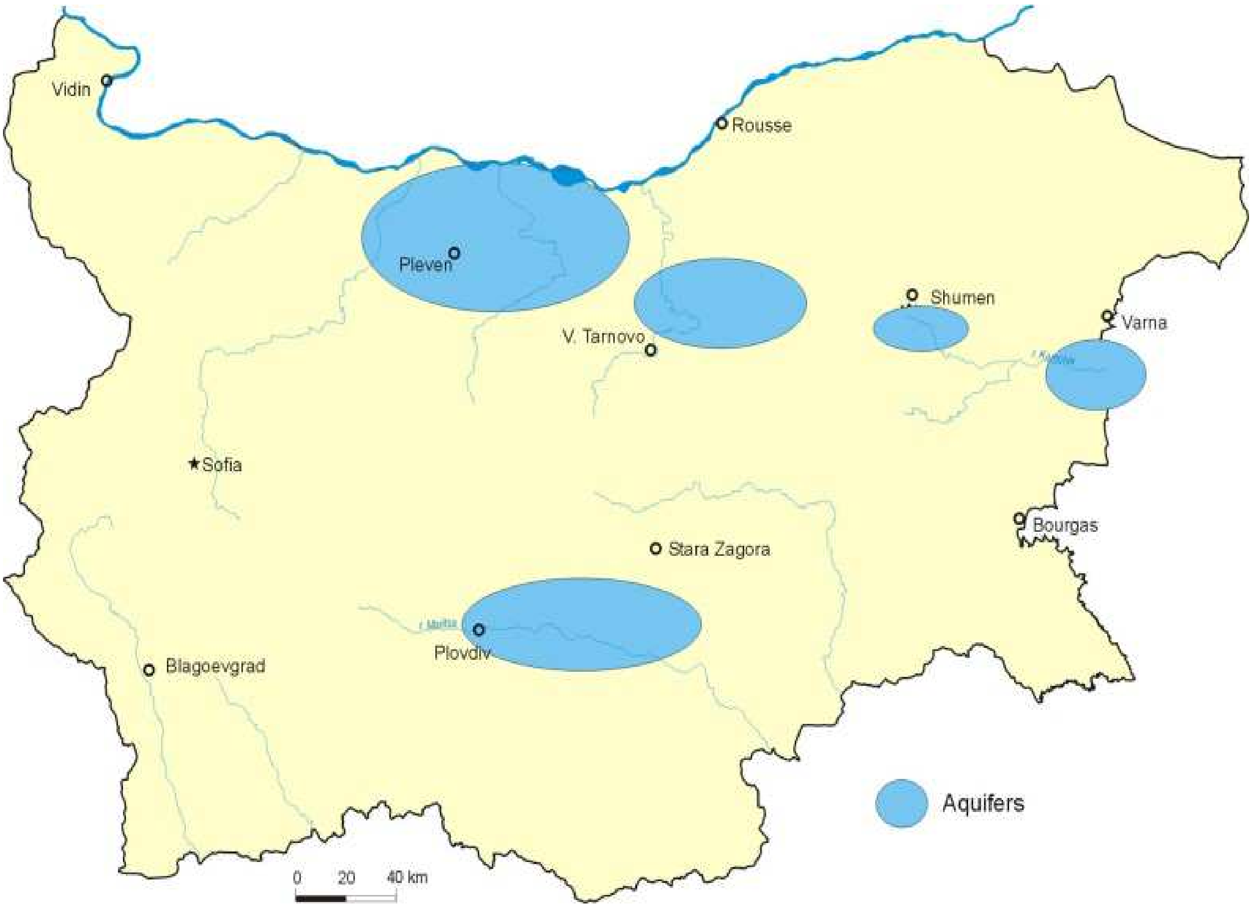


FIG. 2.8. Location of saline aquifers for CO_2 disposal in Bulgaria. Source: [2.21].

Hydrocarbon fields: a total of 12 oil and gas fields have been discovered in Bulgaria. All are located in the northern part of the country in the Moesian platform and the adjacent Forebalkan (Fig. 2.9). Most of them are already depleted or in the final exploitation stage. Yet, most of them do not have the required depth (800–2500 m) for an effective CO_2 disposal. Only in two gas fields (Tchiren and Galata) is the depth appropriate for CO_2 disposal. However, the Tchiren field was converted into a subsurface gas storage in 1974 and is still operating. For the Galata gas field, located offshore, good opportunities for CO_2 disposal are expected (excellent reservoir parameters and very favourable depth). However, there are two restrictions regarding the use of this field for CO_2 disposal: its capacity is low and there is a great interest for its conversion into a gas storage facility.

Unmined coal beds: most of the unmined coal beds occur in Bulgaria at shallow depth and are not favourable for safe injection of CO_2. Deeper coal bearing formations (>800 m), suitable for CO_2 disposal, exist only in two fields: Dobudja and Bobov Dol.

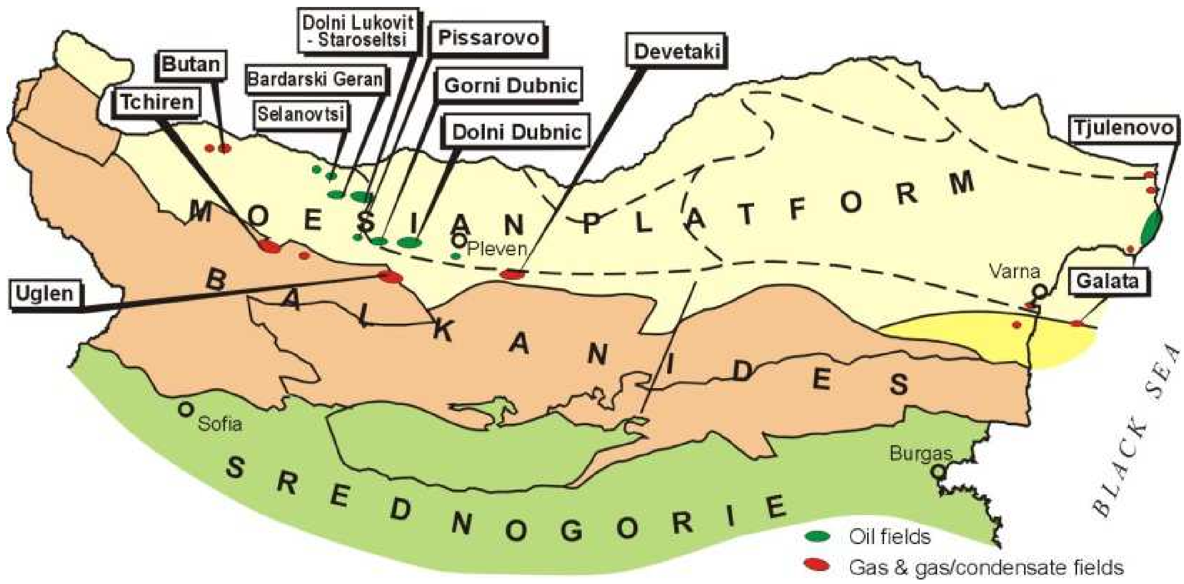


FIG. 2.9. Oil and gas fields in Bulgaria. Source: [2.22].

Radioactive waste disposal

The radioactive waste site selection procedure in the country is carried out by the Geological Institute of the Bulgarian Academy of Sciences. As shown in Fig. 2.10, three potential zones have been outlined [2.23]:

- In the north-western part of the country, located in the Lom depression and related to the Neogene loess-clay formation, for LLW and ILW deep disposal;
- In the southern part of central north Bulgaria, located in the Southern Moesian platform margin and central Forebalkan, related to the Lower Cretaceous (Hauterivian) marl formation for HLW disposal and near surface LILW repository;
- In the southernmost part of the country, located in the Sakar zone and related to a granite plutonic formation for LILW.

2.3.1.2. Brief comparison of disposal options for CO_2 and radioactive waste

The comparison of geological features between the selected sites for CO_2 disposal (Fig. 2.8) and nuclear waste disposal (Fig. 2.10) is shown in Table 2.2.

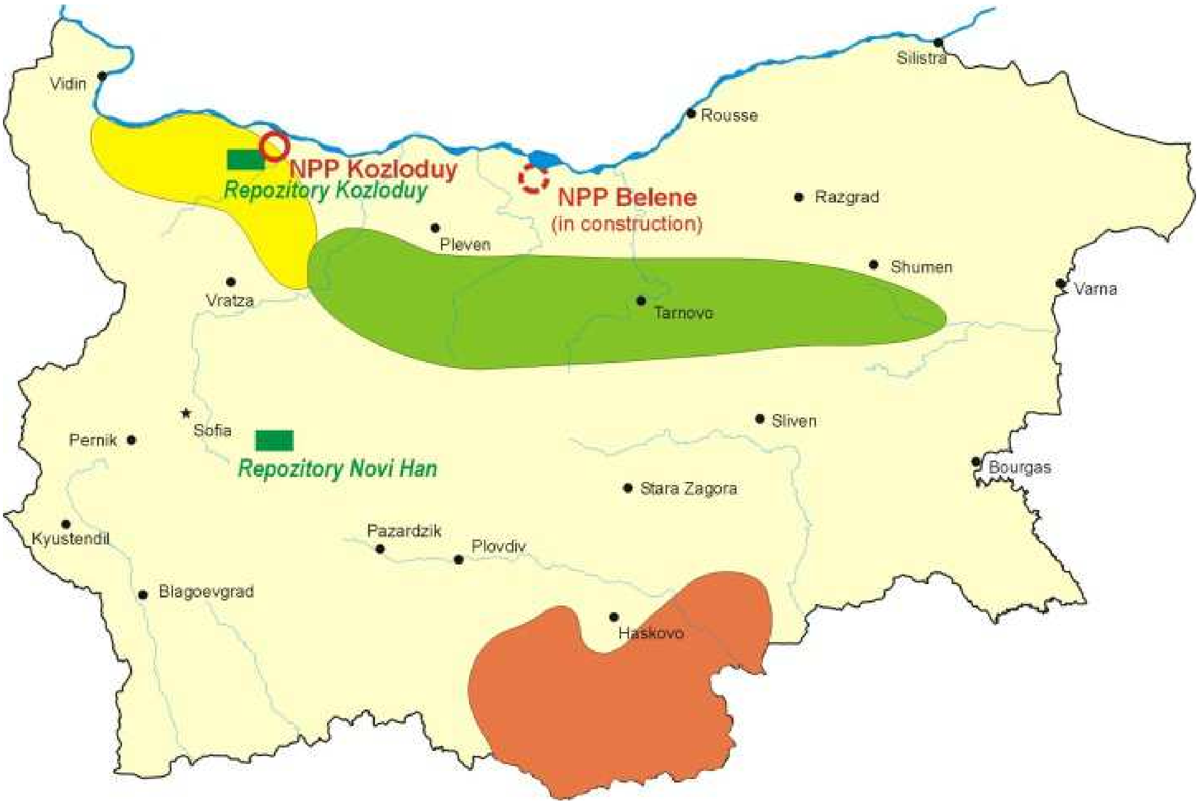


FIG. 2.10. Potential zones for radioactive waste disposal in Bulgaria.

The large spreading of a thick sedimentary succession in the whole northern part of Bulgaria (Moesian platform and Forebalkan), in the Bulgarian offshore area and in some zones of southern Bulgaria (Thracian depression), as well as of the igneous rocks (effusive and intrusive) in southern Bulgaria, offer good geological opportunities for geological disposal of CO_2 and construction of an underground radioactive waste repository for LILW, which has not yet been done.

Three options are considered for geological disposal of CO_2. The first option, *saline aquifers,* offers the highest CO_2 disposal potential in the country. Six local zones and two individual structures have been identified as appropriate for CO_2 disposal so far (Fig. 2.8). The second option is *depleted hydrocarbon fields*. Of the 12 hydrocarbon fields in the country, only two gas fields (Tchiren and Galata) have the appropriate depth for CO_2 disposal. However, the Tchiren field was converted into a subsurface gas storage facility in 1974 and the Galata offshore field, which has low disposal capacity, is also of great interest for conversion into a gas storage facility. The third option is *unmined coal beds,* deeply buried unmineable coal seams (>800 m) found only in two regions: Dobudja in the north-eastern part of the country and Bobov Dol in the south-west.

The radioactive waste disposal site selection procedure in the country is carried out by the Geological Institute of BAS. Three potential zones have been identified (Fig. 2.10): *in the north-western part of the country* the Neogene loess-clay formation for LLW and ILW deep disposal; *in the southern part of central north Bulgaria* the Lower Cretaceous marl formation for a HLW disposal and near surface LILW repository; and *in the south-eastern part of the country* granite plutonic formation for LILW.

TABLE 2.2. COMPARATIVE ASSESSMENT OF DISPOSAL FACILITIES FOR CO_2 AND RADIOACTIVE WASTE IN BULGARIA

Aspects	CO_2 disposal	Radioactive waste disposal
Location	Onshore & offshore	Onshore
Host rock	Sedimentary rocks D_2, T_1, J_2, J_3 –K_{1val}, Pg_2^{2-3} (karstified and fractured carbonates, coarse grained clastics)	Sedimentary (N and $K_{1\ haut}$) and Igneous rocks (granite plutonic)
Depth (m)	Up to 2,200–2,500 m	Up to about 400–600 m
Type disposal	Injection into deep saline aquifers, depleted gas reservoirs, unmined coal seams	Underground disposal facility with ventilation shafts, tunnels and disposal chambers. Multibarrier disposal concept.
Form of disposal	Injection	SF and HLW will be disposed in multilayer containers with stainless steel canister and carbon steel overpack. Chambers and tunnels will be later sealed using bentonitic buffer and backfill.
Volume to store	Yet to be specified	Yet to be specified
Pressures	Above 80 bars	Close to atmospheric pressure
Permeability	As good as possible	Practically no permeability
Hydrogeology	Hydrogeology is controlled by dynamics in pore space; partly influenced by faults, fracture, etc.	Hydrogeology is controlled by flow in fractures, as less as good. Diffusion process important for retardation.
Groundwater	Saline	Depends on the depth and site
Trapping mechanism	Structural and zonal entrapment; possible sorption in coal	Multibarrier concept, system of engineered and natural barriers placed between the wastes and the biosphere
Seismicity (magnitude MSK*)	1–3, exceptionally 4	1–3, exceptionally 4
Tectonic	Different for each site	Site dependent
Capacity	2690 Mt	>10 000 t to be stored (presumed)
Compress strength	-	-
Thickness of isolating rock zone	Depends on selected site, principally at least 80–100 m	Depends on the depth of disposal
Seals	Impermeable dense sediments (Clay stones, evaporates, etc.)	Combination of engineered barriers (bentonite buffer and backfill) and natural barriers (host rock)

Note: *The Medvedev-Sponheuer-Karnik (MSK) scale is a macroseismic intensity scale used to evaluate the severity of ground shaking on the basis of observed effects in an area of the earthquake occurrence.

2.3.2. Cuba

The construction of the first NPP in Cuba began more than two decades ago, but it has been temporarily stopped. The LLW and ILW is foreseen to be deposited in a geological repository located in the central part of the country. The estimated amount of radioactive waste and SF for two WWER-440 reactors with 40 years operation is 20 000 m^3. Another 230 m^3 radioactive waste comes from the utilization of radioisotopes in medicine, industry and research.

The production of electricity in Cuba is based on the use of fossil fuels. Power plants produce about 50% of the CO_2 emissions in the country [2.24]. Total annual GHG emissions are 24.3 Mt CO_2-eq. Cuba produced only 0.09% of the global CO_2 emissions and occupies the 75th position in the world ranking [2.25].

The interest in the geological disposal of CO_2 from the developed oil industry is growing, but no action has been taken. Cuba is a signatory of the Kyoto Protocol and is interested in initiatives that contribute to the reduction of GHGs.

2.3.2.1. Geological opportunities for CO_2 and radioactive waste disposal

The geological structure of Cuba is very complex, consisting of superimposed rock complexes of different compositions [2.26]. The adequate form to implement CCD is in sedimentary formations, where depleted gas and oil fields are located. On the other hand, the adequate geological formation for radioactive waste disposal is in igneous formations (Fig. 2.11).

The selected sites for CO_2 and radioactive waste disposal are also shown in Fig. 2.11. Both zones are characterized by seismic stability and there are no important geological faults. According to the lithological formation, seismic oscillations occur in the range of 0.2–1.3 for the limestone, 0.6–1.4 for the loam and 1.2–2.1 for clays and clay soil [2.27]. The CO_2 and radioactive waste disposal sites are located in the zone with number 18 and 15, respectively, where the increase of the seismic intensity (ΔI) is 1.3.

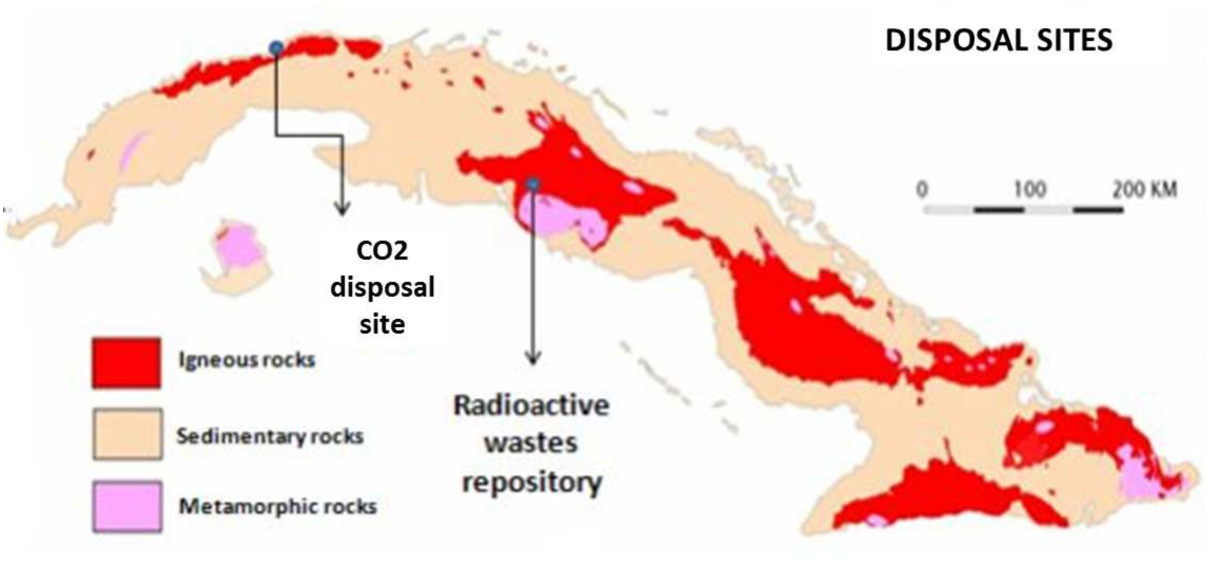


FIG. 2.11. Distribution of the rock complexes in Cuba.

CO_2 disposal

The selected disposal site is a depleted gas field. The productive gas trap is in the trusted dome scale fold. The geological formation with adequate conditions for CO_2 disposal is the Cacarajícara geological formation (K_2 cmp-maa$_2$) at an average depth of 1320 m. The sequence consists of conglomerates in the base and top, gravelstone, marl, limestone, calcarenite, wakestone and mudstone. The reservoir parameters are porosity of about 9% and permeability between 0.1 and 1.96 mD, although the recovery curves show values of up to 5 mD.

The regional seal of the reservoir is the Manacas geological formation (Pg_1^{2-3} – Pg_2^1), presented by olistostromes type chaotic sequence with clasts of different types (loamy siliceous rocks, serpentinites, limoareniscas, limestone), all within a clay-shale matrix with 18% water saturation.

The reservoir strata have a pressure value of 138 atm (standard atmosphere) at a depth of 1310 m, indicating a gradient of 1.05 on the hydrostatic pressure. The geothermal step is 43.8 m/°C and the geothermal gradient is 2.28°C/100 m. The reservoir water was classified as chlorine-calcium with salinity of 32 g/l, density is 1,023 g/cm^3 and pH is 7.5.

The estimation of the potential capacity of the depleted reservoir for CO_2 disposal was made by taking into account two methods of production calculations of the gas resources. The capacity of the reservoir was estimated to be around 74.4 million m^3.

Radioactive waste disposal

The geology of the Cumanayagua region is dominated by igneous rocks where the selected radioactive waste disposal site is located. It is related to a massive igneous complex (plutonic and volcanic) at 20 m underground surface [2.28]. The granodioritic-granitics geological formation is crossed by a complex of dikes with a thickness less than 2 m. The rocks are massive, although there is a system of cracks that cut in different directions. Due to high impermeability, the drainage is largely subordinate to the existing crack network.

The disposal site is located in a foothill area of average height, 50–70 m above sea level, which eliminates the risk from flooding or other events. This area has also favourable conditions for its accessibility.

A groundwater Upper Cretaceous complex of igneous rocks (granodiorites) with a very low permeability (10^{-2}–10^{-3} mD) is developing throughout the area. Groundwater levels are at depths of up to 9.24 m. The aquifer is associated with weathering and fracture zones and it is not powerful. This aquifer does not extend through the entire area.

The main physical geological phenomena in this area are fracturing. The belt of Manicaragua granitoids, as a whole, constitutes an independent unit separate from the neighbouring units (amphibolites mabujina, volcanogeno-effusive complex Cretaceous) by steep dipping faults, whose activity was apparent only during the Late Eocene.

2.3.2.2. *Brief comparison of disposal options for CO_2 and radioactive waste*

The geological comparison between the selected sites for CO_2 disposal and LILW disposal is shown in Table 2.3. The CO_2 disposal site is related to the depleted natural gas reservoir, located in the north-western part of the country. The LILW disposal site is situated in the igneous massive spread in the central part of the country. It is noted that the proposed radioactive waste disposal facility in Cuba is a near surface facility; therefore, the overall comparison with CO_2 disposal cannot be related to the comparative analyses presented for other countries.

In Cuba, the construction of an underground radioactive waste repository for LILW has not yet started, but it is an objective of the Cuban nuclear programme. The case is similar for the geological disposal of CO_2: disposal options are being considered, but have not been implemented so far. The safe disposal of CO_2 and radioactive wastes is very important to ensure their proper management. The oil industry shows an increasing interest in the detailed knowledge of CCD technology for possible future EOR based on CO_2 injection into oil producing fields.

The mountains, valleys, plains and adjacent seas to Cuba are based on bedrock of various nature, with the presence of sedimentary, igneous and metamorphic rocks. The sedimentary rocks are widespread onshore, on the islands and under the seabed of the island shelf, where limestone predominates. Igneous rocks form the second most widespread area and they are of effusive and intrusive nature.

TABLE 2.3. COMPARATIVE ASSESSMENT OF DISPOSAL FACILITIES FOR CO_2 AND RADIOACTIVE WASTE IN CUBA

Aspects	CO_2 disposal	Radioactive waste disposal
Location	Onshore	Onshore
Host rock	Sedimentary rocks (conglomerates, marl, limestone, calcarenite, wakestone and mudstone)	Igneous rocks (granodioritics, cuarzodioritics and rarely dioritics)
Depth (m)	1310	20
Type disposal	Depleted gas reservoir	Construction and excavation is required. Horizontal disposal chamber.
Form of disposal	Injection	LLW will be conditioned in metal drums of 200 L and adding a concrete container for intermediate level.
Volume to store	About 1 Mt	230 m^3 (+ 20 000 perspective)
Pressures	138 bar	Atmospheric pressure
Permeability	0.01 to 1.96 up to 5 mD	10^{-2} to 10^{-3} mD
Hydrogeology	Controlled by lithological and structural process.	Aquifer associated with weathering and fracture zones in place is not powerful.
Groundwater	At -1270 m (chlorine-calcium, chloride group, subgroup sodium)	At depths of 0.0 to -9.24 m (its origin is through infiltration of water precipitation, this aquifer does not extend to the entire area).
Trapping mechanism	Structural entrapment	Multibarrier concept, system of engineered and natural barriers placed between the wastes and the environment
Seismicity (magnitude MSK)	6.0–7.0 region	6.0–7.0 region (expected <4.5 for the area of the emplacement)
Tectonic	Scale like folds (thrusted sheets in the area adds style to alpine tectonics)	Internal tectonics are relatively simple, consisting mainly of vertical or subvertical normal faults, which divide the massif into irregular polygons.
Capacity	74 million m^3	-
Compress strength	-	620–682 kg/cm^2
Thickness of isolating rock zone	45 m	-
Seals	Stratigraphic (Paleocene deposits) loamy siliceous rocks, serpentinites, limestone) all within a clay matrix.	Natural barriers of igneous rocks from Cretaceous plus artificial formation man-made

2.3.3. The Czech Republic

In the Czech Republic, two nuclear stations are in operation: Dukovany (4 × 400 MW(e)) and Temelín (2 × 1000 MW(e)) (see Fig. 2.12). The operating power reactors (with 3760 MW(e) capacity) are expected to produce about 3800 tHM of SF and more than 20 000 m^3 of radioactive waste (after conditioning), which is not acceptable for the existing near surface disposal facilities.

FIG 2.12. Nuclear facilities in the Czech Republic.

Three research reactors are in operation (10 MW) for scientific purposes at the Nuclear Research Institute Rez plc. and at the Czech Technical University in Prague.

So far, four repositories for LLW and ILW have been commissioned in the Czech Republic:

- *Hostim repository* (closed) for institutional waste;
- *Richard repository* (since 1964) for waste not contaminated by natural radionuclides;
- *Bratrství repository* for waste contaminated by natural radionuclides (^{226}Ra, ^{210}Po, ^{210}Pb, and uranium and thorium isotopes);
- *Dukovany near surface repository* for LLW and ILW (since 1995), located near the Dukovany NPP.

No deep geological disposal facility for radioactive waste has been commissioned in the Czech Republic.

Inventories of GHG emissions in the Czech Republic are shown in Fig. 2.13. In 2006, the total aggregated emissions reduction was almost 23.9%, compared to 1990 level [2.29], [2.30], [2.31], [2.32]. The geographical distribution of the stationary industrial point sources of CO_2 emissions is shown in Fig. 2.14. The shares of CO_2 emissions by industrials sector are presented in Table 2.4. There is no CO_2 disposal facility in operation in the Czech Republic.

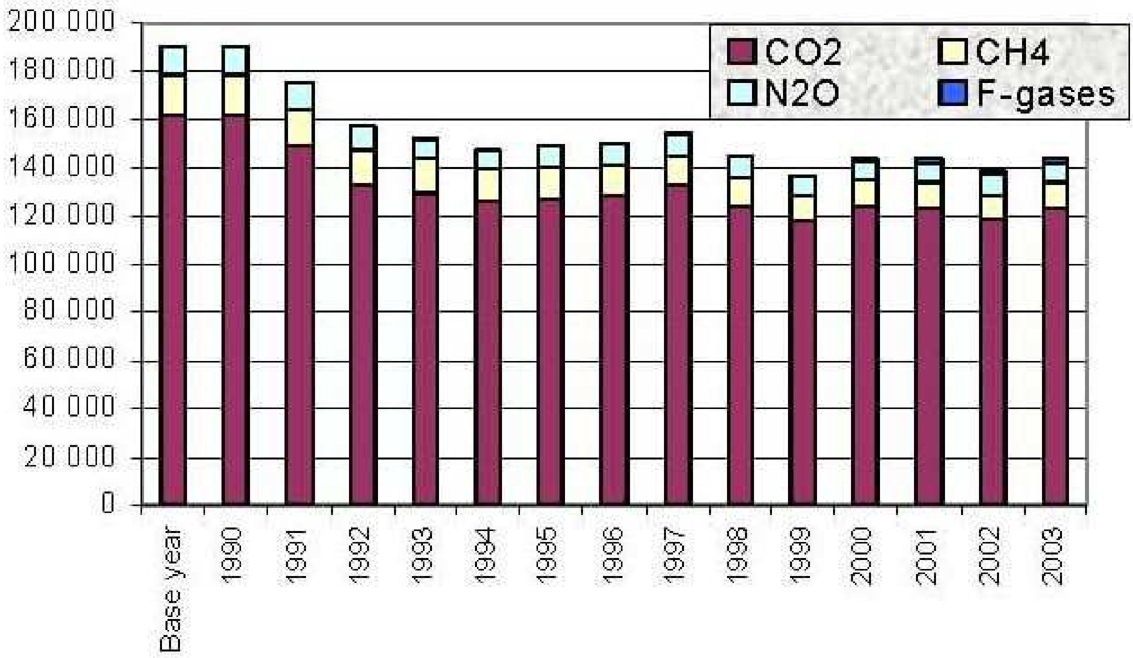


FIG. 2.13. Total GHG emissions in the Czech Republic.

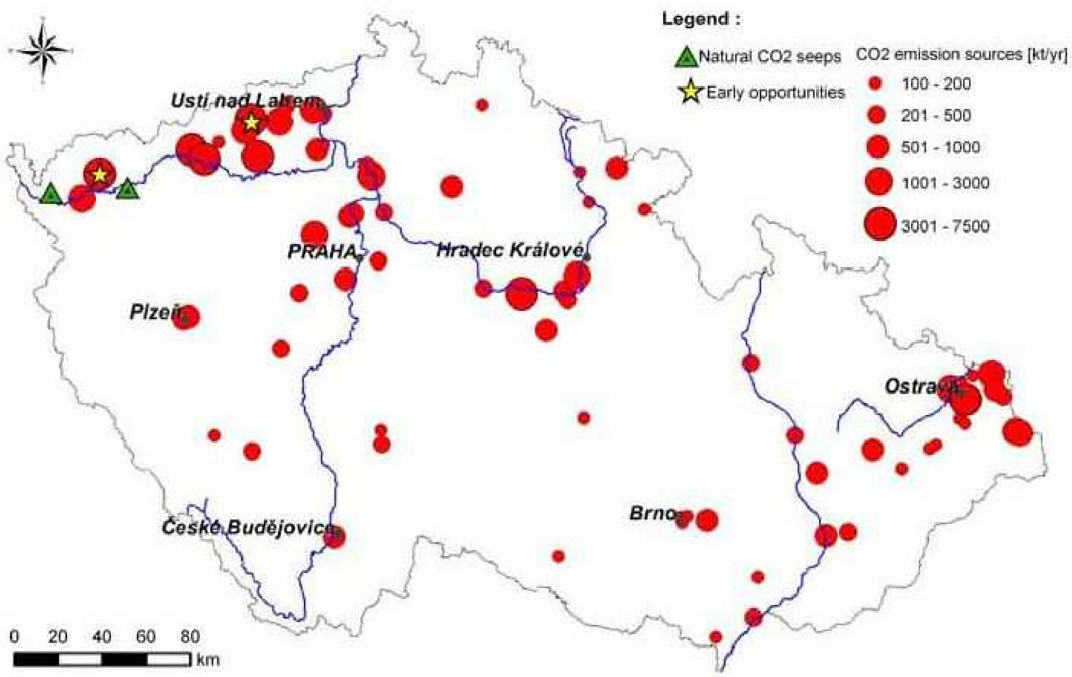


FIG. 2.14. Industrial CO_2 sources in the Czech Republic (kt CO_2- eq). Source: [2.33].

TABLE 2.4. SHARE OF INDUSTRIAL CO_2 EMISSIONS. SOURCE: [2.33]

Sector	Emissions (t/year)	Share (%)	Number of facilities
Power	49 145 177	63.0	25
Heat	8 849 058	11.3	27
Chemicals (other)	4 540 421	5.8	7
Refineries	969 327	1.2	3
Iron and steel	9 866 977	12.6	7
Paper and pulp	454 158	0.6	3
Cement	2 553 038	3.3	5
Other (lime, glass, etc.)	1 652 271	2.1	10
Total	78 030 427	100.0	87

2.3.3.1. Geological opportunities for CO_2 and radioactive waste disposal

CO_2 disposal

In the Czech Republic, CO_2 disposal is only possible onshore. Several locations with suitable CO_2 disposal potential have been found. No detailed exploratory activities have been performed up to now [2.33].

Deep saline aquifers: attention is focused on vertically closed structures with sufficient sealing and significant pore volume capacity. Altogether, 22 potentially suitable structures were identified, 17 of them in the Carpathians and five in sedimentary basins of the Bohemian Massif. The geographical distribution of the considered structures is shown in Fig. 2.15. The Bohemian Massif aquifers are mainly Upper Carboniferous (Stephanian) sandstones and arcoses, overlaid by Lower Permian (Autunian) clay stones. The Carpathian Foredeep aquifers are Lower Miocene sandstones sealed by Upper Miocene clay stones. In the Flysch zone, the aquifers are related to Miocene sandstones.

Depleted oil and gas fields: more than 40 oil and gas fields in the country have been registered up to now. The depleted fields are located in the eastern part of the Czech Republic, in the Carpathians (Vienna Basin, Carpathian Foredeep and Flysch zone). Many of the partially depleted oil fields in the Vienna Basin and the Carpathian Flysch zone are suitable for CO_2 based EOR. Their operator shows an interest in using this technology, but there are no available sources of CO_2. Hydrocarbon fields in Czech Republic suitable for CO_2 based EOR and coal measures with ECBMR potential are described in Hladik et al. [2.33].

Unmined coal field are another option for CO_2 disposal. Some unmined pit coal measures in the Upper Silesian basin and in the Permian-Carboniferous Central Bohemian basins are interesting for potential ECBMR.

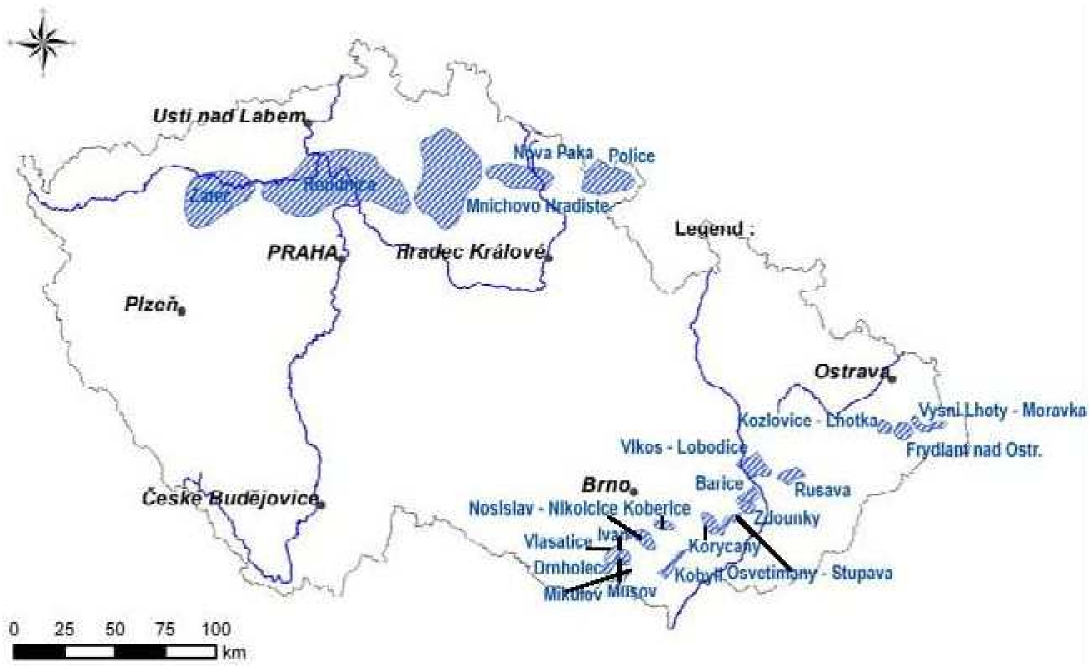


FIG. 2.15. Geographical distribution of suitable aquifers for CO_2 disposal in the Czech Republic. Source: [2.33].

The CO_2 disposal capacity estimates for the Czech Republic are shown in Table 2.5. The disposal capacity has been calculated according to the methodology of the Carbon Sequestration Leadership Forum (optimistic) and the US Department of Energy (conservative) [2.34], in the frame of the EU GeoCapacity project [2.35].

TABLE 2.5. CO_2 DISPOSAL CAPACITY ESTIMATES IN THE CZECH REPUBLIC. SOURCE: [2.35]

CO_2 disposal capacity	Pyramid class	Conservative estimate (Mt)	Optimistic estimate (Mt)
Disposal capacity in aquifers	Effective	766	2863
Disposal capacity in hydrocarbon fields	N/A	33	33
Disposal capacity in coal fields	Effective	54	54
Total disposal capacity estimate	Effective	853	2950

Radioactive waste disposal

The territory of the Czech Republic is characterized by the Bohemian Massif in the west and the Carpathians in the east. A significant part of the area is formed by crystalline rocks. The deep geological repository for radioactive waste will most likely be constructed in the granite massif, in a seismic stable area. Other host rocks have also been considered in the past, such as clay formations and metamorphic rocks.

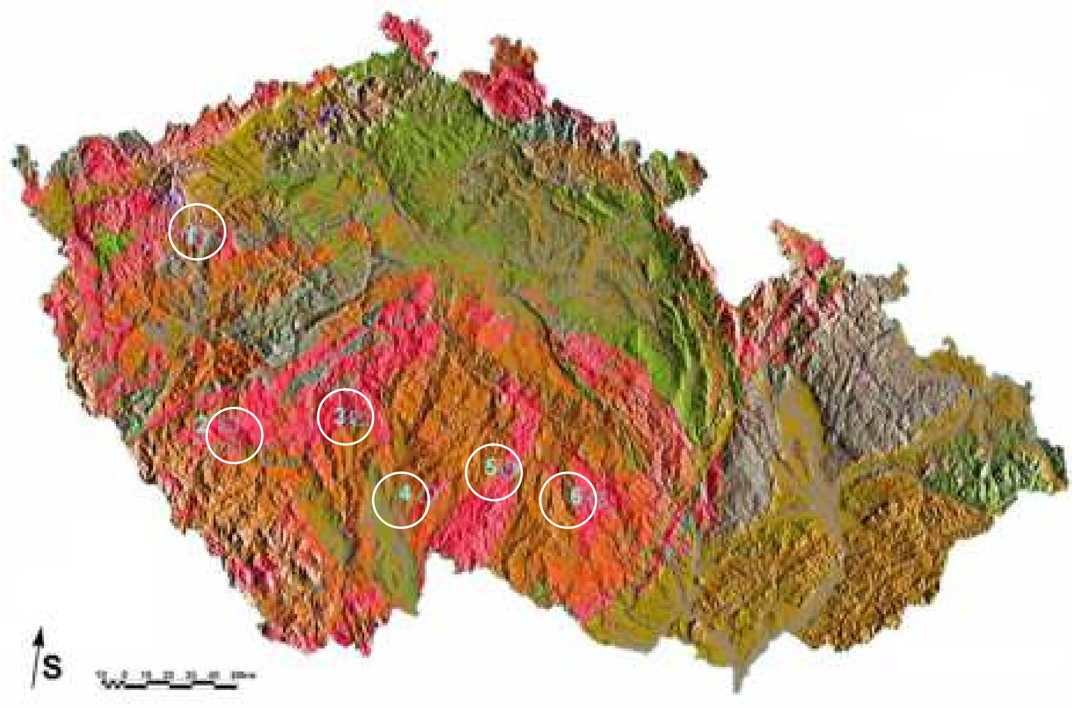


FIG. 2.16. Suitable host rock regions for deep geological repository for radioactive waste in granitic rocks (granitic massifs shown in red). Source: [2.36].

Several potential regions were identified around 2002 (Fig. 2.16). However, no detailed research activities have taken place so far. In 2009, several military areas were searched for potential siting locations [2.36].

Research has been performed at test sites and in the laboratory at the Nuclear Research Institute, Czech Technical University and other institutes. In the Czech Republic, the disposal of radioactive waste is supposed to be final (no retrieval in the future is expected) and direct (no reprocessing of SF). Carbon steel containers will be used as an overpack of fuel rods, local bentonite (Rokle) is foreseen as backfill and buffer. A granite site was chosen for disposal (depth of approximately 500 m), and a multinational deep geological repository can be considered. Alternative technologies (transmutation, etc.) should be evaluated as well. Safety of the disposal would be considered up to a million years.

2.3.3.2. Brief comparison of disposal options for CO_2 and radioactive waste

In the Czech Republic, some regions have been selected for radioactive waste disposal and CO_2 disposal, without any conflict for the disposal option. Their comparative analysis is presented in Table 2.6.

TABLE 2.6. COMPARATIVE ASSESSMENT OF DISPOSAL FACILITIES FOR CO_2 AND RADIOACTIVE WASTE IN THE CZECH REPUBLIC

Aspects	CO_2 disposal	Radioactive waste disposal
Location	Onshore	Onshore
Host rock	Probably deep saline aquifers, depleted gas reservoir, unmined coal measures (coal seams)	Crystalline rock (most probably granitic ones)
Depth (m)	Below 800 m	400–600 m
Type of disposal	Deep saline aquifers, depleted gas reservoir, unmined coal seams	Underground disposal facility, comprising access and ventilation shafts, tunnels and disposal chambers. Multibarrier disposal concept.
Form of disposal	Injection	SF and HLW will be disposed of in multilayer containers with stainless steel canister and carbon steel overpack. Chambers and tunnels will be later sealed using bentonite buffer and backfill.
Volume to store	To be specified	7647 t spent fuel assemblies and 4300 t other waste (presumed)
Pressures	Above 80 bars	According to the depth of the disposal (400–800 m)
Permeability	Site specific, to be specified	Site specific, to be specified
Hydrogeology	Hydrogeology controlled by diffusion in pore space; partly influenced by lithological features (faults, fracture, boreholes).	Hydrogeology controlled by advective flow in fractures in crystalline rocks. Diffusion process important for retardation.
Groundwater	Saline	Depends on the depth and site of disposal.
Trapping mechanism	Structural and chemical entrapment; possible sorption (coal)	Multibarrier concept, system of engineered and natural barriers placed between the wastes and the biosphere
Seismicity (magnitude MSK)	1–3, exceptionally 4 (both tectonic and mining origin)	1–3, exceptionally 4 (both tectonic and mining origin)
Tectonic	Site dependent, has to be defined	Site dependent, has to be defined
Capacity	Capacity to store 2950 Mt	Higher than 13 000 t to be disposed of (presumed)
Thickness of isolating rock zone	To be defined	Depends on the depth of disposal
Seals	Stratigraphic: most probably low permeable caprock (clay stones)	Combination of engineered barriers (bentonite buffer and backfill) and natural barriers (host rock)

Several geological options have been identified for CO_2 disposal. The deep saline aquifers have the highest potential, with an emphasis on identifying vertically closed structures with sufficient sealing and significant pore volume capacity. Altogether, 22 potentially suitable structures were identified. Many of the partially depleted oil fields in the Vienna Basin and the Carpathian Flysch Zone are suitable for CO_2 EOR, but there is no suitable source of CO_2 in the neighbourhood. The unmined pit coal measures are also interesting, especially for ECBMR. Such structures can be found mostly in large parts of the Upper Silesian Basin and in the Central Bohemian Basins.

For radioactive waste disposal, several host rocks have been considered: clay formations, crystalline and metamorphic rocks. The deep geological repository for radioactive waste will most likely be constructed in the granite massif, in a seismically stable area. The disposal of radioactive waste will be based on the multibarrier concept, i.e. the safety function is supported by the waste form, carbon steel container, bentonite buffer and backfill and host rock. The concept for the radioactive waste repository is to be located in tunnels at depth below 400 m, which will be connected by a vertical shaft for the transport of workers and materials.

2.3.4. Germany

2.3.4.1. Geological opportunities for CO2 and radioactive waste disposal

Geological research for possible disposal sites for radioactive waste has been going on for decades. The search for potential CO2 disposal opportunities started much later, but a range of research projects were undertaken over the past 10–15 years.

CO_2 disposal

The total amount of CO_2 emitted in Germany in 2008 was 833 Mt, about one third of which came from transportation and small users. Germany has several onshore options for the deep disposal of CO_2 [2.37], [2.38]:

Depleted gas fields are considered by some experts as an appropriate disposal option for CO_2, because their caprocks have successfully retained gases for several million years. This option appears to be the cheapest for geological disposal of CO_2 due to the fact that the existing gas infrastructure and technology can be used with relatively few modifications, and also because the use of CO_2 injection will enhance recovery of residual natural gas (enhanced gas recovery – EGR). However, there are only 66 gas fields of adequate size to dispose of CO_2 in Germany. An average German gas field would be large enough to hold roughly 3–5 years of the CO_2 emissions of a typical German large lignite power plant which emits roughly 8–10 Mt CO_2 per year. Depleted gas fields are mainly located in the north and middle German sedimentary basins in Permian and Triassic sandstones. Their disposal capacity is estimated to be around 2.75 billion t CO_2.

Depleted oil fields are, in principle, also appropriate. However, because of their limited disposal capacity, about 130 Mt, their overall contribution to CO_2 disposal is very limited.

Deep saline aquifers have the largest potential for CO_2 disposal, because of their widespread distribution in the country. Their waters have high salt content and are located at great depth; thus, they are not suitable for drinking or agriculture purposes. During the last years, the Institute for Geosciences and Natural Resources (Bundesamt für Geowissenschaften und

Rohstoffe) has continuously reviewed the CO_2 disposal capacity of saline aquifers and has estimated that it would be between 6.3–12.8 billion t in the three large areas of Norddeutsches Becken, Oberrheingraben und Alpenvorland-Becken.

In the framework of the project CO_2SINK in Ketsin (close to Potsdam, Brandenburg), CO_2 is injected into a saline aquifer, located in a geological dome structure at a depth of about 650 m. The aquifer is overlain by shale caprocks of about 240 m thickness, which, together with the anticline structure, ensure limited migration of the CO_2. The targeted reservoir formation is porous sandstone. CO_2 has been injected since 2008, and in October 2010, the total injected quantity reached 40 000 t.

Research on CO_2 injection and disposal in a depleted gas field was planned to take place in the Altmark natural gas field, which is Europe's second largest gas field. CO_2 was to be injected in the depleted natural gas reservoirs in order to test the technical feasibility. The Altmark field is located in the state of Sachsen-Anhalt in north-eastern Germany, roughly 120 km south-east of Hamburg. The reservoir, made of red sandstone and siltstone with shale layers, is located at a depth of 3.5 km and has a wide range of porosity and permeability. Above the reservoir, there is the Zechstein salt bedrock with a thickness of several hundred meters, which forms an effective caprock. The disposal capacity is estimated to be up to 508 Mt, roughly 1/5 of the total disposal potential in German gas fields. However, the project was discontinued.

2.3.4.2. Radioactive waste disposal

Different options have been considered for the final disposal of radioactive waste in Germany [2.39]:

- The Gorleben salt exploration mine, situated in the district of Lüchow-Dannenberg in Lower Saxony, about 100 km south-east of Hamburg and about 2 km south of the Elbe River;

- The former iron ore mine Konrad, located in Salzgitter in central Germany between Hannover and Magdeburg;

- The former salt mines Asse and Morsleben, located not far from Helmstedt city, near the border between the Federal States of Lower Saxony and Saxony-Anhalt.

For waste with negligible heat generation, the heat release per waste package is in the milliwatt range. Consequently, the temperature increase in the surrounding host rock caused by this heat release is minor. In the case of heat generating waste, however, the heat release is in the kilowatt range, which can cause a temperature increase in the adjoining host rock of more than 100°C. To cool down the waste and to optimally use the available repository space and, thus, to minimize the costs of final disposal, heat generating waste is placed in interim surface storage facilities for several decades, which are located in Ahaus and Gorleben.

In 1963, the Federal Government of Germany issued a recommendation to use salt formations for radioactive waste disposal. In 1973, planning for a national repository started, and, in 1976, the Atomic Energy Act was amended to make such disposal a responsibility of the Federal Government.

The Federal Government, through the Federal Office for Radiation Protection (BfS), is responsible for building and operating final repositories for HLW, but progress in this has been hindered by opposition from State Governments. The German Society for Building and Operation of Final Disposal for Waste Material (Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH – DBE) is the company actually building and operating the Konrad and Gorleben repository projects, and operating the former Morsleben Repository for Radioactive Waste (ERAM).

For the Gorleben site, no suitability statement has been released as of mid-2014. This can only be issued after the Lower Saxony Ministry of Environment, as the competent government agency and licensing authority, has approved the site plan. A precondition for the conclusion of the plan approval process is the completion of underground exploration and its analysis, as well as the completion of a site specific safety analysis. In July 2009, new repository criteria came into force, replacing rules dating from 1983. Authorities may now license a HLW repository only on the basis of a scientific demonstration that the waste will be stable in the repository for one million years. In addition, all HLW disposed of in any German repository must be retrievable during the entire period of repository operation.

Following an exhaustive site selection process, the state government of Lower Saxony, in 1977, declared the Gorleben salt dome to be the location for a national centre for radioactive waste disposal. It is now considered a possible site for geological disposal of HLW. This will comprise about 5% of the total waste volume and 99% of the radioactivity. A pilot conditioning plant is there. Some EUR 1.5 billion was spent from 1979 to 2000 for researching the site. Work then stopped due to a political edict, but the government approved resumption of excavation in 2009.

The two shafts, Gorleben 1 and 2, with depths of 933 m and 840 m, respectively, are situated in the centre of the salt dome, which is approximately 14 km long and 4 km wide, and has been explored with regard to its suitability to host a final repository for all types of radioactive waste. The salt dome top (salt wash surface) is about 250 m below the surface, the salt dome base lies at a depth of 3200–3400 m.

Several levels have been excavated in the Gorleben exploration mine. In addition to the actual exploration level at 840 m below the surface (i.e. 820 m below sea level), where the geoscientific and geotechnical exploration was carried out until the beginning of the moratorium on October 1, 2000 (exploration suspended), additional 'technical' levels were excavated at depths of 820 m (return air level), 880 m (haulage level) and 930 m (shaft undercut). In total, about 7 km of drifts and galleries (with a volume of approximately 234 000 m^3) have been excavated, and geological and geotechnical boreholes with an overall length of about 16 km have been drilled.

Of the five exploration areas originally planned in the north-eastern part of the salt dome, only exploration area 1 (EB 1) and the infrastructure area near the shafts (workshops, work and disposal rooms) have been completed so far. In addition to the two shafts, hoisting plants and their corresponding surface installations, such as the shaft hall, loading bay and personnel walkway, the 28 ha grounds include an office building and a building housing changing/shower facilities, a store with workshops, a drill core storeroom and further technical installations. The salt dump for the mined salt is situated about 1 km from the mine site. So far, about 600 000 t of salt have been deposited here.

The Asse salt mine repository, licensed by federal and state agencies in the 1960s and 1970s, is now closed. It received wastes from 1967 to 1978. In 2010, the Federal Office for Radiation Protection decided that, due to technical problems, the wastes should be removed from it, and then rejected an alternative of filling the facility with concrete to provide a stable matrix for the 126 000 drums there. The waste is likely to be moved to Konrad.

The former iron ore mine Konrad was originally owned by the Salzgitter AG (Aktiengesellschaft – corporation). Mining was terminated for economic reasons in 1976 and, due to the favourable geological conditions of the mine's site, an extensive geoscientific exploration and investigation programme to assess the site's suitability to host a final repository for radioactive waste with negligible heat generation was carried out.

The Konrad site was licensed in 2002 for LILW disposal, but legal challenges were mounted. These were dismissed in March 2006 and again in April 2007. A construction licence was issued in January 2008. Konrad will initially take some 300 000 m^3 of wastes: 95% of the country's waste volume, with 1% of the radioactivity. The DBE plans for it eventually to accommodate 650 000 m^3 of wastes. It is expected to be operational by about 2014. The two shafts Konrad 1 and 2 are about 1.5 km apart. Their surface infrastructure has a total of 6 levels with a horizontal extension of about 1.7 × 3.0 km.

Konrad Shaft 1 is used for hoisting excavated rock, supplies and personnel. This shaft also serves as air intake for the mine ventilation, necessary for the personnel and the operation of more than 50 vehicles. Exhaust air is discharged to the surface via shaft Konrad 2.

The Morsleben radioactive waste repository (*Endlager für radioaktive Abfälle Morsleben – ERAM)* was built in a former salt and potash mine. This LILW repository was licensed in 1981, relicensed after the reunification of Germany, and was closed in 1998. It is being stabilized with concrete. A salt deposit with a length of 40 to 50 km and an average width of 2 km had been developed at the end of the 19th century. Potash and rock salt were mined for about 70 years, leaving a mine with a length of 5.6 km and a maximum width of 1.4 km. The shaft Bartensleben was sunk to a depth of 524 m and four main mining levels were excavated underground. Mining was done by using the room and pillar method without backfill. This produced caverns with a length of up to 120 m and a width and height of up to 40 m. The galleries used for the final disposal of waste until 1998 are situated in the mine's periphery.

2.3.5. India

2.3.5.1. Geological opportunities for CO_2 and radioactive waste disposal

Peninsular India spans an area of about three million km^2 and has a wide spectrum of rock types, ranging in age from Achaean to recent in varying geographic, climatic and seismic domains. The major geological units are represented by granites, granite gneisses and associated basement crystalline, Deccan basalts, Proterozoic meta-sedimentary basins and Indo Gangetic alluvium plains. The large size of the country and the occurrences of a wide spectrum of lithologies offer a large potential for the disposal of both radioactive waste and CO_2. Additionally, large areas are available that have been identified as possible locations for CO_2 disposal along the coast of India for offshore and onshore disposal.

Site selection criteria for radioactive waste disposal are very stringent, mainly due to the required higher consideration of safety aspects as compared to sites for CO_2 disposal. Hence, the size and locations of areas being studied for radioactive waste disposal are quite limited.

From the seismicity point of view, only areas falling in seismic zones I and II and characterized by very low horizontal accelerations (<0.2 g) are being considered for this purpose. In addition, such areas should have very low groundwater and surface water potential, lean forest covers and a low population density.

Radioactive waste disposal

India, as a policy, has selected granites as the preferred host rocks for hosting a deep geological repository for the permanent disposal of vitrified HLW [2.40], [2.41], [2.42], [2.43], [2.44], [2.45]. Granites cover about 20% of the total area of the country (0.60 million km^2). India undertook extensive studies on granites in an area of about 0.1 million km^2 from 1990 to 2000 to generate a large database on petro-mineralogical, rock mechanical, thermal, geochemical and radiochemical properties of these granites. During these studies, granites, especially those associated with relatively younger magmatism (500–700 Ma), such as the Malani Igneous Suite of north-western India and few older granites (~2500 Ma) occurring in central and eastern India, have emerged as promising regions due to their suitability as host rock for deep geological repository. Among these, Bundelkhand granites and Dongergarh granites are noteworthy.

Stage I: In the initial stage, most of the information pertaining to geology, hydrogeology, structure and aspects related to socio-political and economic factors is derived from secondary datasets, mainly published reports. The information is integrated in a geographical information system (GIS) environment, preferably on a scale of 1:250 000. During this integration, ample use of satellite imageries, such as LISS III and IV, obtained from the Indian Remote Sensing (IRS) series is made to generate information on gap areas. Such an approach has yielded valuable information on the distribution of seismic events, lineaments, major hydro-geological zones, geological and structural details. Close evaluation of a series of such large scale maps helped in carving out three major regions occupied by granites in north-western, central and eastern India, with an area of approximately 15 000, 60 000 and 15 000 km^2, respectively.

During this exercise, certain specific criteria were established to undertake additional assessments of these regions. These assessments, with the help of secondary datasets, rendered a few zones, each measuring 100–150 km^2, in area for follow-up investigations.

Among the criteria related to tectonics and instability, the location of the area within notified seismic zones in the Indian shield along with the occurrences of major structural discontinuities like faults, shears, etc., have been assigned the greatest importance. Consequently, regions falling in seismic zones I and II with a maximum ground acceleration of 0.1 and 0.2 g, respectively, were considered. Among the geological characteristics, homogeneity of the rock mass with sufficient depth persistence (~1 km) and area extent (minimum of 4 km^2) have been considered to be essential requirements. Additionally, the absence of intrusive chemical durability, good mechanical and thermal strength and mineral deposits are important to consider. The criteria taken into account under hydrogeology mainly included the absence of surface water bodies and high rain fall, lower recharge and relief. The presence of a sparse population, distance from industrial and commercial areas, better accessibility and favourable political climate constituted socio-economic criteria during this stage of investigation. Based on these criteria, a total of 20 attributes were identified. The information, generated through secondary as well as primary data sets involving the application of satellite and selected field checks, was subsequently transformed into numerical entities by assigning a maximum score and a suitable weighing factor to individual attributes. The aggregated score points, obtained by all attributes for all the zones, reveal their relative suitability.

Stage II: The second stage of the investigation mainly focuses on large regions in the zones identified in the first stage of the investigations and essentially involves data generation on scales of 1:50 000 and 1:25 000. These zones, 100–150 km^2 in size, were divided into 5 × 5 km^2 grids and subjected to systematic evaluation by means of studies on geomorphology, soil thickness, rock types, weathering pattern, jointing, land use, etc. The attributes were again transformed into numerical values, using the same procedure as in the first stage, to undertake a comparative assessment of these zones. Sensitivity analysis was also performed to gauge the relative importance and impact of individual attributes. One of the zones was taken up for third stage investigations, involving geological and structural mapping with the help of a plane table and a theodolite, pitting and trenching on a 1:5000 scale. The focus of this activity was on outcrop mapping, correlation studies and the demarcation of heterogeneity, such as dikes, shear zones, detailed fracture mapping and short borehole drilling. These studies helped in demarcating an area of a few km^2 wherein the geological and topographic features are in conformity with the requirements. This zone has been explored with the help of ground geophysics as well as borehole geophysics. The core samples retrieved from array based boreholes have been subjected to intensive studies on fracture characteristics and other rock mass parameters, such as core loss, rock quality designation, rock mass rating, etc.

Stage III: The third stage investigations are marked by very detailed geological and structural surveys on a 1:1000 scale and geophysical surveys, such as resistivity, gravity, magnetic, etc., on 50 × 50 m grid. The data obtained through such surveys were analysed using software like Magmod and three dimensional site models have been produced up to a depth of 1 km. These models have been validated by deep drilling (600 m). The representative cross section of the zones, delineated through the above investigations, is depicted in Figs. 2.17 and 2.18.

While granites are India’s preferred host rocks for permanent radioactive waste disposal, shale also constitutes a potential option for hosting deep geological repository. Shale with significant thickness is known to occur in some of the Proterozoic basin, namely the Vindhyan System of central India and the Cuddapah System of Andhra Pradesh in southern India. Among these shales, the Shirbu shales in the Vindhyan System and the Tadpatri shales in the Cuddapah System show some degree of potential as host rocks.

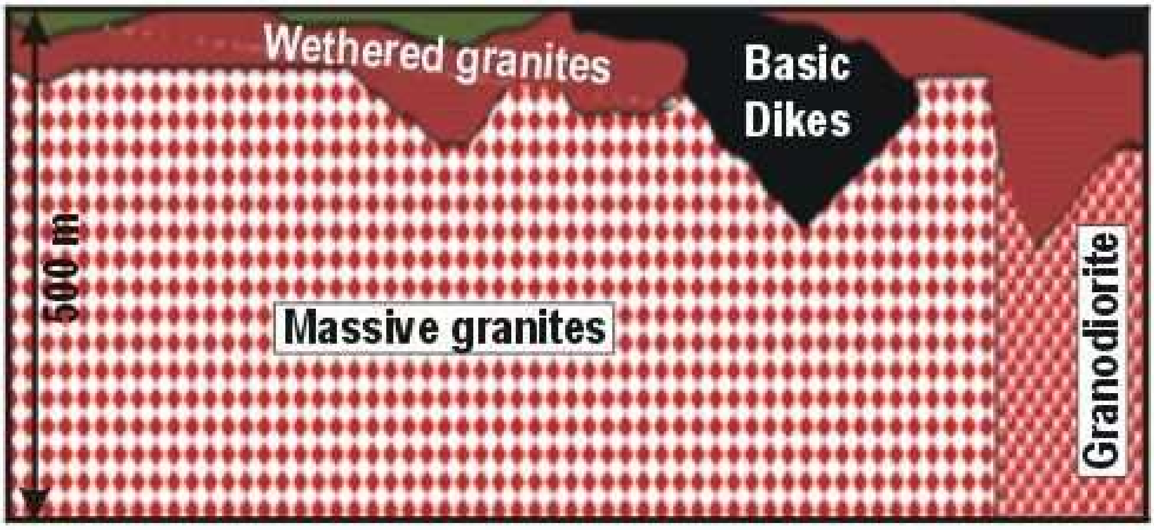


FIG. 2.17. A 500 m deep profile.

FIG. 2.18. Very high quality, fracture free granites at depth, granites from depth of 450 m.

CO_2 disposal

India has a large range of geological settings with the potential for disposal of CO_2 (Fig. 2.19).

Deep saline aquifers have considerable potential, particularly offshore, and on the margins of the Indian peninsula, particularly in Gujarat and Rajasthan in north-western India. There is also good aquifer disposal potential in the areas surrounding Assam in north-eastern India. The total disposal potential is in the order of 300–400 Gt. However, these formations are located almost 750–1000 km from the five large point sources of CO_2, each with annual emissions more than 5 Mt. Therefore, CO_2 disposal may prove costly, due to transport costs.

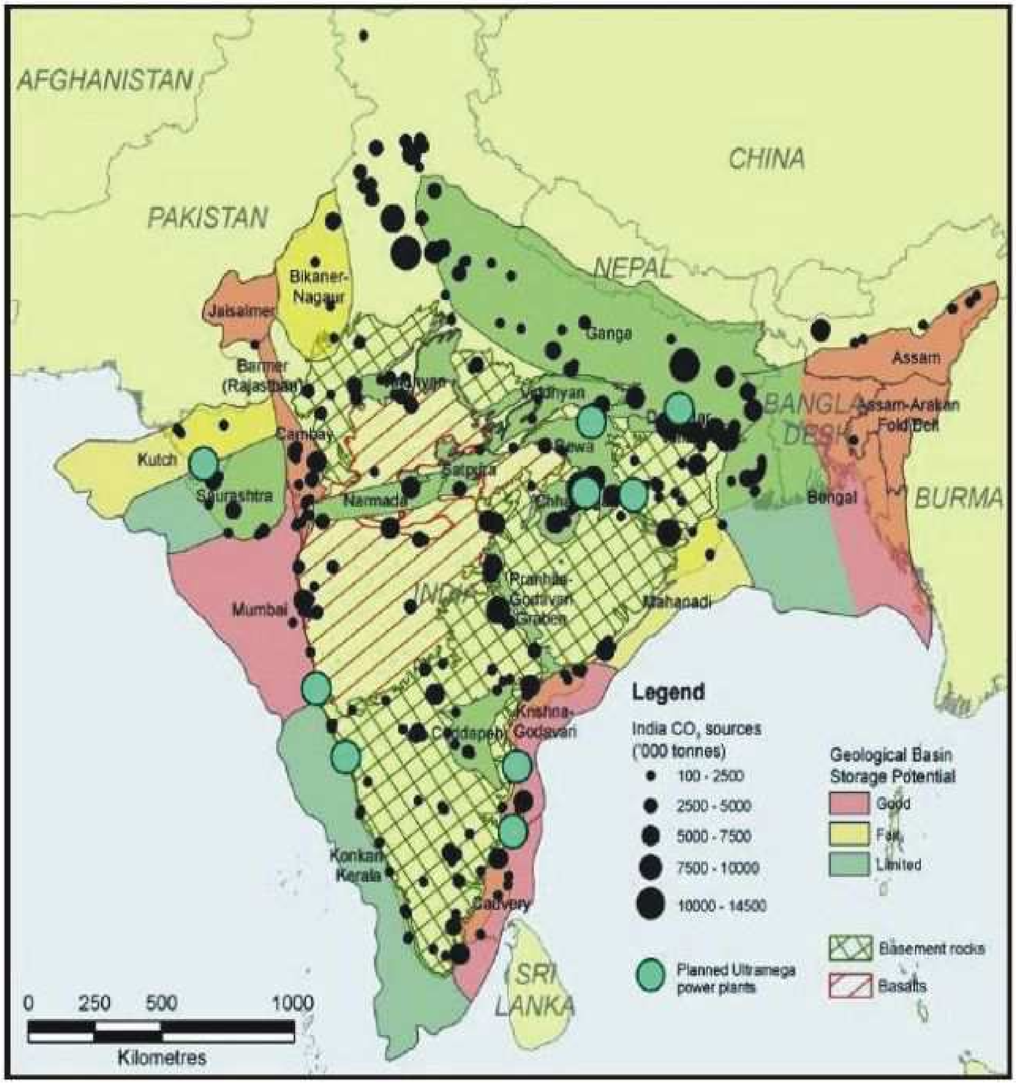


FIG. 2.19. Potential CO_2 disposal sites. Source: [2.46].

The Indo-Gangetic foreland running along the Himalayan mountain chain is an important potential disposal area, because it occupies almost 25% of the total geographic area of the country. The Ganges area has a basin area of 186 000 km^2, with a large thickness of caprock composed of low permeability clay and siltstone.

The exploration in the Indo-Ganges alluvial plains has established the presence of shallow and deep saline aquifers up to a depth of 1000 m and more in a stretch of 700 km from Meerut to Ghazipur in Uttar Pradesh in central India. The proximity of the sources to the potential disposal site makes it a good candidate for a pilot project.

Recoverable coal reserves in India are the fourth largest in the world. However, these can be easily mined and will be used as fuel. Thus, the potential for CO_2 disposal in coalbeds at depths above 1200 m could be severely constrained. An indicative calculation for the International Energy Agency Greenhouse Gas R&D Programme suggests that the disposal potential could be on the order of 345 Mt CO_2 in the major coalfields nationally, and none of the coalfields are estimated to have the capacity to dispose of more than 100 Mt CO_2 [2.46]. If CO_2 disposal in coal reserves proves practical at depths greater than 1200 m, very large potential (e.g. in the Cambay Basin and down dip to the east of the Rajmahal coalfields) could be exploited.

Oil and gas fields occur in three main areas in India: Assam and the Assam-Arakan Fold Belt in north-eastern India, the Krishna-Godavari and Cauvery basins in south-eastern India and the Mumbai/Cambay/Barmer/Jaisalmer basin in the west-north-western part of India. The total disposal capacity in oil and gas fields is estimated to be between 3.7 and 4.6 Gt CO_2. Many Indian oil and gas fields are relatively small for CO_2 disposal. Only a few fields (e.g. the Bombay High field, offshore Mumbai) are thought to have ample disposal capacity for the lifetime emissions of a medium sized coal fired power plant. However, some of the recent offshore gas discoveries may have potential.

The thick basaltic formations in India, spreading over an area of 50 000 km^2, have also emerged as attractive host for CO_2 disposal, with a capacity of approximately 300 Gt CO_2. Basalts will be the caprock, the injection of CO_2 will be in the underlying sedimentary rocks. The important characteristics of basaltic formations include: (a) large and continuous areal extent, (b) large combined thickness of the flows (>1 km in some localities), (c) favourable interflow features, (d) reactive silicate mineral assemblages, and (e) Mesozoic sediments containing Fe-Mg-Ca silicate mineral. They all suggest that the Deccan Continental Flood Basalt Province could possibly constitute a large scale reservoir for CO_2 that needs to be confirmed by studies.

Ultramafic rocks, due to their high content of magnesium oxide (MgO), sodium oxide (Na_2O), calcium oxide (CaO), etc., have also been considered as potential host rocks for CO_2 disposal. India has large occurrences of such rocks throughout its territory. The larger part of the promising ultramafic rocks are found in southern India and are represented by the well studied greenstone belts of Dharwar Craton.

2.3.5.2. Brief comparison of disposal options for CO_2 and radioactive waste

In India, several potential host rock complexes of large expansion are considered with respect to their suitability for hosting disposal facilities for radioactive waste and CO_2. A comparison of geological features for CO_2 and radioactive waste disposal is shown in Table 2.7.

Basalts are very suitable for the disposal of radioactive waste and CO_2. They have very good sorption characteristics. The thick basaltic formations have emerged as a very attractive host for CO_2 disposal with a disposal capacity of about 300 Gt.

Ultramafic greenstone belts have enormous potential for CO_2 disposal, because of their capacity for mineral carbonation. However, it has not been considered as a host rock for radioactive waste, due to its porosity and permeability related to fracturing.

Argillaceous rocks have been under consideration as potential host rocks for radioactive waste disposal facilities, but not for the geological disposal of CO_2.

Granites are one of the most preferred host rocks for radioactive waste disposal facilities worldwide, mainly due to superior mechanical and thermal properties. Similarly to other crystalline rocks, they are not under consideration for the geological disposal of CO_2.

Deep saline aquifers have a considerable potential for CO_2 disposal, particularly on the coast and on the margins of the Indian peninsula. The Indo-Gangetic foreland is an important potential disposal site for CO_2, as it occupies almost 25% of the total country area.

Coal seams: the fourth largest recoverable coal reserves in the world are found in India. However, much of this coal is easily mined and will be used as fuel. This means that the potential for CO_2 disposal at depths above 1200 m could be severely constrained.

Oil and gas fields occur in three main areas in India: the Assam-Arakan fold belt in north-eastern India, the Krishna-Godavari and Cauvery basins in south-eastern India and the Mumbai/Cambay/Barmer/Jaisalmer basin area. The total disposal capacity in oil and gas fields is estimated to be between 3.7 and 4.6 Gt CO_2. Some of the recently discovered offshore gas fields may also have potential.

2.3.6. The Republic of Korea

The major emitting sources for CO_2 disposal projects include power generation, steel mills, petrochemical and cement industries. The energy sector emitted 498.5 Mt CO_2 that was 83.9% of the total emission amount in 2005. For power generation by coal, the total CO_2 emission by five electric power companies under the Korea Power Corporation was 118 Mt. The next largest emitter was a steel mill company, POSCO: 30 Mt CO_2 from the Pohang factory and 35 Mt from the Gwangyang factory. In the petrochemical industry, 20 Mt CO_2 was emitted from the southern part of Ulsan city [2.47].

Since 1977, the Korea Hydro and Nuclear Power Company (KHNP), the major generator of LILW, has been operating 20 NPPs (16 pressurized water reactors and four CANDUs) and generated about 67 000 drums (200 L) of LILW. Korean LILW has been classified into four categories: dry active waste, evaporator bottom, spent resin and spent filter. The accumulated LILW can be broken down as follows:

- Dry active waste – 36 600 drums (56%);
- Evaporator bottom – 19 000 drums (28%);
- Spent resin – 9700 drums (14%);
- Spent filter – 1600 drums (2%).

This LILW is stored in temporary disposal facilities at each of the NPP sites and has been prepared for disposal in the final repository in the Wolsong site.

TABLE 2.7. COMPARATIVE ANALYSES OF DISPOSAL FACILITIES FOR CO_2 AND RADIOACTIVE WASTE DISPOSAL IN INDIA

Aspects	CO_2 disposal	Radioactive waste disposal
Location	Onshore/offshore	Onshore, granites of north-western, central and eastern India evaluated
Host rock	Alluvium, mine coal seams, depleted oil strata, basalts, ultramafic rocks	Granites
Depth (m)	~1000 m	~500 m
Type disposal	Injection in porous formation, mineral carbonation in basalts	Disposal in pit mode in specifically designed disposal pits and backfilling by clay sand admixtures
Form of disposal	Injection	Emplacement
Volume to store	Approximately 600 Gt	Geological disposal facility is being designed for 10 000 waste filled canisters
Pressures	Varies from host rock to host rock and with depth as well	10–12 MPa lithostatic pressure, 1–2 MPa hydrostatic pressures
Permeability	Not yet known	10^{-9} to 10^{-13} mD
Hydrogeology	Saline aquifers	Groundwater flows through fractures
Groundwater	Saline	Site dependent, but mostly high silica and Na to retard waste glass corrosion
Trapping mechanism	Structural entrapment, mineral carbonation	Multibarrier concept: Canisters to be placed in pits, clay buffers to insert between the canisters and host rock
Seismicity (magnitude MSK)	Not yet known	Regions with maximum horizontal ground acceleration of <0.2g; i.e. seismic zones I and II of the country
Tectonic	Preferably away from the active zones	Min. 200 km away from active tectonic zones like plat boundaries
Capacity	Multiple sites with varying capacity ranging from 10 Gt to 500 Gt	10 000 waste filled steel canisters
Compress strength	Approximately 20 MPa for sandy units, 150–200 MPa for basalts	150–200 MPa
Thickness of isolating rock zone	Variable and host rock dependent	50 m
Seals	Impervious caprock	Impervious host rock and clay seals

2.3.6.1. Geological opportunities for CO_2 and radioactive waste disposal

CO_2 disposal

The main reason for the slow progress in CO_2 disposal in the Republic of Korea is the perception that no good disposal site exists. The Republic of Korea established a disposal site data bank in 2008. This showed that no onshore sedimentary basin favourable for CO_2 disposal could be identified in the country since 1970. However, there are several large sedimentary basins offshore, such as the Kunsan, Jeju and especially Ulleung basins, see Fig. 2.20 [2.48] [2.49]. However, it will take long time to calculate the precise CO_2 disposal capacity of the Ulleung basin.

Figure 2.20 also shows the major CO_2 emitters. Power generation plants are concentrated in the western coastal area to supply electricity to the Seoul metropolitan area and in the southern coastal area to supply electricity to the second largest city of Busan [2.48]. The only major emitter close to the Ulleung basin is POSCO, the steel mill. The power generation plants for CCS are located more than 150–200 km from the Ulleung basin. Assuming that the costs of CCS in Korea are almost the same as in other countries, the reduction of the transportation costs is the main task, in order to raise the competitiveness of the project. Thus, it is reasonable to consider selecting CO_2 disposal sites near major emitters, if possible, to minimize transport costs.

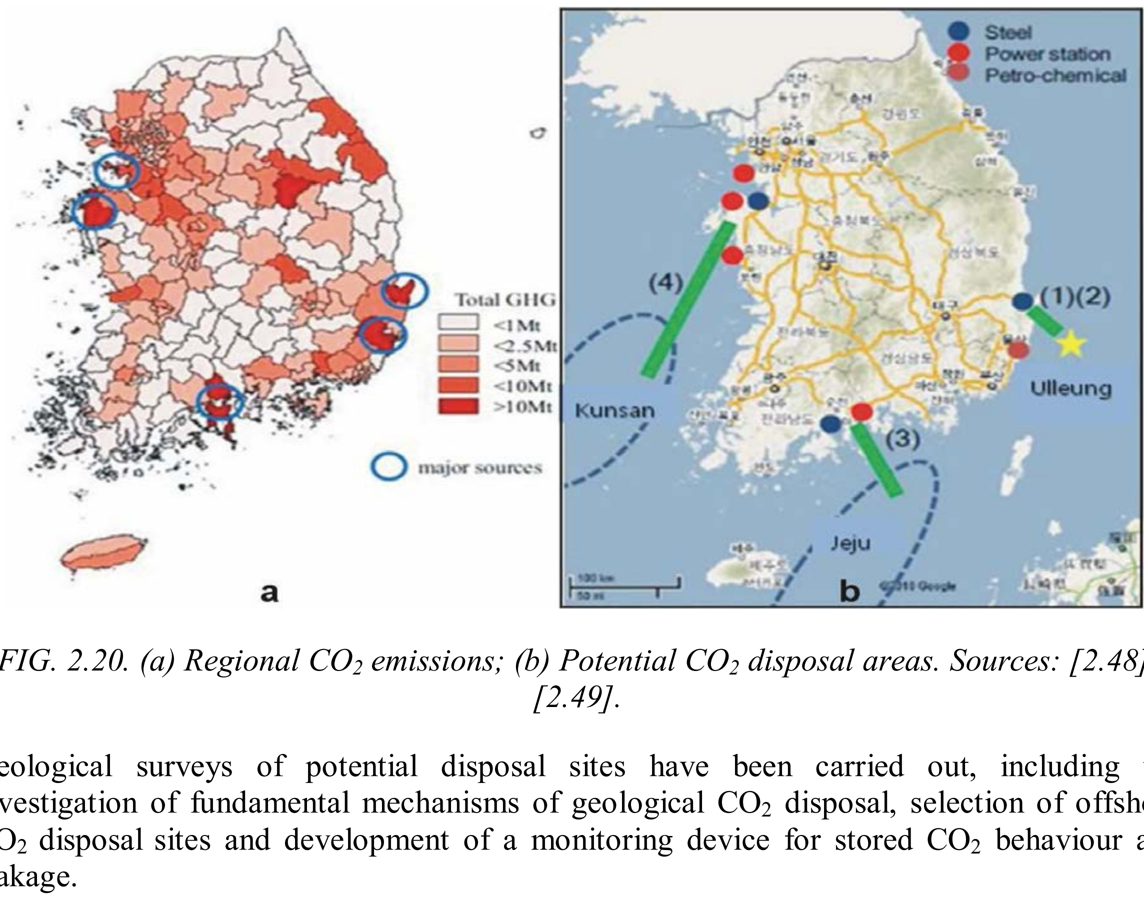


FIG. 2.20. (a) Regional CO_2 emissions; (b) Potential CO_2 disposal areas. Sources: [2.48], [2.49].

Geological surveys of potential disposal sites have been carried out, including the investigation of fundamental mechanisms of geological CO_2 disposal, selection of offshore CO_2 disposal sites and development of a monitoring device for stored CO_2 behaviour and leakage.

In order to study potential disposal sites, the Ministry of Knowledge Economy (MKE) plans to perform a 217 000 km 2-D seismic survey and 20 well drillings by 2018 (Table 2.8) [2.48].

TABLE 2.8. SEISMIC SURVEYS AND WELLS COMPLETED AND PLANNED OFFSHORE. SOURCE: [2.48]

Basin	Mining Block	Seismic survey (L-km)		Wells	
		1970–2008	2009–2018 (planned)	1970–2008	2009–2018 (planned)
Kunsan	6	57 951	67 000	6	6
Jeju	4	95 802	74 000	14	6
Ulleung	2	137 711	76 000	23	8
Total	12	291 464	217 000	43	20
		508 464		63	

The Kunsan Basin. There are several basins in the Yellow Sea. The South Yellow Sea Basin, which is located between eastern China and the South Korean peninsula, is subdivided into the Northern and Southern South Yellow Sea basins by a central uplifted area [2.49]. The Northern South Yellow Sea Basin is one of a number of Mesozoic Cenozoic non-marine, back-arc, trans-tensional rift or pull-apart basins distributed along a general north-east-south-west trend in China and the Yellow Sea. It is filled with mainly Cretaceous and Cenozoic non-marine clastic sediments. The eastern part of it is divided by structural highs and faults into the south-west, central and north-east subbasins. In the Republic of Korea, the eastern part of the Northern South Yellow Sea Basin is called the Kunsan Basin [2.49].

It is clear that the depositional environment in the Kunsan Basin is fluvial and lacustrine. This is similar to the depositional systems in other extensional Cenozoic basins. The lithological column from the investigation indicates numerous potential reservoir-seal pairs [2.49]. An environmental interpretation of paleogeography would better illustrate the potential for disposal into the saline reservoir.

The Ulleng Basin, in particular, has many favourable disposal structures which show sandstone reservoirs of more than 200 m thickness, including the Gorae-V structure of the Donghae-1 gas field, which has been producing natural gas since 2004 (see Table 2.9).

TABLE 2.9. SUMMARY OF PROSPECTS FOR GEOLOGICAL CO_2 DISPOSAL IN BLOCK VI-1 OF THE ULLENG BASIN. SOURCE: [2.50].

Well	Top Depth MD m	Bottom Depth MD m	Gross Interval	Gross sand	Net sand	Net sand/ Gross	Porosity	Water Saturation
Dolgorae II	1920.0	2437.0	517.1	216.8	214.3	0.41	0.236	0.942
Gorae V-3	1886.0	2560.0	674.1	466.9	417.9	0.62	0.192	0.948
Gorae 7-1X	1675.0	2100.0	425.1	319.8	303.2	0.71	0.253	1.0
Gorae V-4	1871.9	3001.1	1129.3	482.6	339.7	0.30	0.154	0.585

It might be possible to find a large potential structure for CO_2 disposal if the data base of 23 drilling wells, including several gas discovery wells and 2-D and 3-D seismic data were utilize. In addition to reprocessing existing seismic data, new data acquisition is expected in the near future. One deep sea drilling in the Ulleung basin is also planned in the joint exploration activity by the Korea National Oil Corporation (KNOC) and Woodside of

Australia. Although a couple of potential areas in the southern Ulleung basin would be recommended based on our current knowledge, more work needs to be done to assess their potential for CO_2 disposal.

Radioactive waste disposal

In June 2005, the Korean government issued a Public Notice on the selection of a candidate site for a LILW repository, and the city of Gyeongju was selected as the final candidate site based on voting by its residents. In June 2006, a rock cavern repository was selected as the disposal method in the first stage. In January 2007, the Korea Hydro and Nuclear Power Company, Ltd., (KHNP) submitted an application for a permit to construct and operate the proposed LILW repository and received conditional permission at the end of August 2008. KHNP performed site characterization from November 2005 to July 2008 for the permit for the construction and operation of the Wolsong LILW repository. The geological characterization, including hydrology, hydrogeochemistry and groundwater flow was performed as part of the site characterization.

The Wolsong site is located in the south-eastern coastal area of the Korean Peninsula, about 26.5 km south-east of the city Gyeong-Ju. The area, approximately 1.1 × 1.8 km, is bounded by a national park to north and the Wolsong NPP to south. The site area consists of a rolling hill topography with a general eastward slope toward the East Sea.

The detailed geology of the site area mainly consists of Cretaceous sedimentary rocks (Ulsan Fm) and Tertiary plutonic and intrusive rocks (59.8±1.8 Ma). The Ulsan Fm is predominantly alternating strata of mudstone, siltstone and sandstones. The plutonic rocks consist of diorite, granodiorite and biotite granite, gradually changing from basic to acidic composition away from the contact with sedimentary rocks.

The silo location is mainly composed of granodiorite, similar to diorite, with biotite dominance and an increase of quartz and K-feldspar. Diorite changes to granodiorite, with a decrease in the amount of opaque minerals and an increase in grain size. Diorite, in fine grains, is mainly composed of plagioclase, K-feldspar, biotite and amphibole. A small distribution of biotite granite is found in the northern part of the site. Rhyolites are intruded into the Cretaceous sedimentary rocks and the Tertiary granitic rocks. They are distributed as the largest outcrop in the northern area and as dykes in the southern area. The trachytic andesites are distributed on a small scale as an intermediate dyke.

The hydrogeological characterization of the site was performed from the surface and subsurface investigations, including geological mapping and analysis, drilling investigation and hydraulic testing, geophysical survey and interpretation [2.51]. The north-south trend of the mountain ridge in this region leads the surface water run-off and groundwater to flow eastward toward the East Sea, depending on its hydraulic gradient. The Wolsong site, characterized by the hydro-structural model of Rhén et al. [2.52], consists of one hydraulic soil domain (HSD), three hydraulic rock domains (HRD) and five hydraulic conductor domains (HCD). The HSD shows overburdens and the uppermost fractured rock mass and its thickness ranged from 5 to maximum of 24–28 m; the hydraulic conductivity is about 2.6–4.5 × 10^{-6} m/s, and the mean bulk porosity is 0.34%. The HRD consists of small fracture zones, discrete fractures, and a less permeable rock matrix between the fractures. The three HRDs are primarily defined according to fracture orientation [2.52]. The effective hydraulic conductivity of the upper regime (7.7 × 10^{-8} m/s), which is bounded around -120 m depth from the ground surface, is more permeable than the lower regime (6.6 × 10^{-8} m/s) [2.51]. The permeability of the silo regime is 4.5×10^{-8} m/s. The HCD includes the deterministic fracture zone. The hydraulic conductivity of HCD is assumed to be 1×10^{-7} m/s [2.51].

The groundwater chemical condition at the Wolsong site were investigated by cations and anions analyses of groundwater samples from 12 boreholes, three surface water samples and one seawater sample. The isotopes O-18, H-2, H-3, C-13, and S-34 were also analysed to trace the origin of water and solutes. The groundwater types of the site were represented by $Ca\text{-}Na\text{-}HCO_3$ and $Na\text{-}Cl\text{-}SO_4$, which was caused by sea spray and water rock interaction. The high concentration of sodium (Na) in the groundwater resulted from ion exchanges.

For the redox condition of the groundwater, the values of dissolved oxygen and oxidation / reduction potential (Eh) are decreasing with depth, indicating that the reducing condition is formed in deeper groundwater. In addition, the high concentrations of iron (Fe) and manganese (Mn) show that the redox condition of the groundwater is controlled by the reduction of Fe and Mn oxides. The analysis results of O-18 and H-2 show that the surface water and groundwater originated from precipitation. The tritium concentrations of the groundwater decreases with depth, but high concentrations of tritium indicate that the groundwater was recharged recently.

Geochemical research on the rocks and minerals of the site was also carried out in order to provide data for geochemical modelling and safety assessment. The identified fracture filling minerals were montmorillonite, zeolite minerals chlorite, illite, calcite and pyrite. Pyrite and laumontite, which are known as minerals of hydrothermal alteration, were widely distributed, indicating that the Wolsong site was affected by mineralization and/or hydrothermal alteration. Sulphur isotope analysis for the pyrite and oxygen-hydrogen stable isotope analysis for the clay minerals indicate that they originated from the magma. Therefore, it is believed that the fracture filling minerals from the site were affected by the hydrothermal solution as well as the water-rock interaction.

2.3.6.2. Brief comparison of disposal options for CO_2 and radioactive waste

The comparative analysis of disposal facilities in the Republic of Korea is presented in Table 2.10. While details for radioactive waste disposal facilities are presented in the table, most of the parameters for CO_2 disposal facilities are not yet available.

TABLE 2.10. COMPARATIVE ASSESSMENT OF DISPOSAL FACILITIES FOR CO_2 AND RADIOACTIVE WASTE IN THE REPUBLIC OF KOREA

Aspects	CO_2 disposal	Radioactive waste disposal (LILW)
Location	Offshore	Onshore
Host rock	Sedimentary rocks	Granite rocks
Depth (m)	Not determined	130
Type disposal	Injection	Construction and excavation is required.
Form of disposal	Injection	In drums of 200 L (LILW) disposed in six silo type disposal method
Volume to store	Not determined	800 000 drums (x 200L)
Pressures	No information available	Atmospheric pressure
Permeability	No information available	$4.5 \times 10^{-8} \sim 6.6 \times 10^{-8}$ m/s
Hydrogeology	Controlled by lithological and structural process	Controlled by fracture zones in place
Groundwater	No information available	Origin through infiltration of water precipitation; $Ca\text{-}Na\text{-}HCO_3$ and $Na\text{-}Cl\text{-}SO_4$ type, caused by water-rock interaction
Trapping mechanism	Structural entrapment	Multibarrier concept, system of engineered and natural barriers placed between the wastes and the environment
Seismicity (magnitude MSK)	No information available	No information available
Tectonic	No information available	Cretaceous sedimentary rocks and tertiary plutonic rocks and intrusive rocks
Capacity	Not determined	800 000 drums (× 200L)
Compress strength	No information available	No information available
Thickness of isolating rock zone	No information available	No information available
Seals	Stratigraphic within a clay layers	Natural barriers of crystalline host rocks plus engineering sealing

It is noted that the proposed radioactive waste disposal facility is a relatively near surface, silo option. As such, because it is not a true geological disposal facility, it has only limited value in the formal comparison between CO_2 disposal and the geological disposal of radioactive wastes.

Progress has been slow for CO_2 disposal, because of the wide perception that no good site exists. However, good disposal sites may be present in the continental shelf and the analysis of the large amount of geophysical and drilling data is now required. Since 1970, several large sedimentary basins were found offshore such as the Kunsan, Jeju and Ulleung basins.

2.3.7. Switzerland

Nuclear energy and waste: Switzerland currently operates five nuclear reactors located at four sites. The total amount of radioactive waste produced by the five Swiss reactors is expected to be almost 100 000 m^3, of which 7.5% will be SF and HLW. A comprehensive approach has led to the identification of six potential areas with suitable geological conditions for the disposal of radioactive waste [2.18].

Fossil energy and CO_2: With only a very small fraction of electricity produced in Switzerland being from fossil fuel power plants (<5%), the necessity to identify carbon reduction measures such as CCD in the electricity generation sector is not applicable to today's situation. The largest point source emitters of CO_2 in Switzerland are industrial facilities. The options for CO_2 disposal are being assessed by the ongoing Carbon Management in Power Generation (CARMA) research project [2.53], which focuses largely on future energy options.

2.3.7.1. Geological opportunities for CO_2 and radioactive waste disposal

CO_2 disposal

Within the CARMA project, a first appraisal of the potential for deep geological disposal of CO_2 in Switzerland was made by Chevalier and Diamond [2.54], also reported by the Federal Agency for Energy (Bundesamt für Energie – BFE) [2.55]. Following a numerical scoring and weighting scheme on a scale of 0–1, they determined that the combined volumes of the four main candidate aquifers with potentials above 0.6 offer a theoretical, effective disposal capacity of 2680 Mt CO_2. Future fossil fuelled power stations in Switzerland would most probably be natural gas combined cycle plants, due to the lack of inland fossil resources, the existence of natural gas pipelines and the lower CO_2 emissions per kWh of natural gas compared with coal. A 400 MW(e) combined cycle gas power station produces approximately 0.7 Mt CO_2/year (assuming 360 kg/MWh and 5000 hours/year operation). The research concluded that more than sufficient disposal capacity for CCD from electricity generation and other industrial activities exists to serve the needs of many decades. This is, however, only a preliminary study based on the literature, and the actual disposal potential may prove to be very different following more physical geological examinations of the area.

Four options were identified as potentially relevant for the geological disposal of CO_2 [2.55]:

Mineral carbonation: The Swiss Alps contain large quantities of basalt and serpentinite rocks that have suitable chemical compositions for the purpose of mineral carbonation. However, all these rocks are highly metamorphosed, so their intrinsic permeability is virtually zero. Most of the rocks are intensely fractured, and although these fractures could provide access for injected CO_2 to the reactive minerals, they are not sealed above by other impermeable rock formations. Consequently, any injected CO_2 would surely escape before being fixed by chemical reactions with the nearby rocks. Moreover, the necessary temperatures are encountered only at prohibitively deep levels (>4 km). In view of these facts, there appears to be no potential for in situ mineral carbonation as the primary mechanism of CO_2 disposal in Switzerland.

Unmineable coal beds: Seams of coal up to 4 m thick are known at depths of 1550–1750 m, which precludes commercial exploitation. Little direct information is available on the spatial extent of the coal, but the geological setting suggests that the coal is likely to occur in only small areas. From a geological point of view, it would be worthwhile to conduct a pilot study at particular points, but the outcomes are unpredictable at the current state of knowledge. While this option cannot be ruled out for Switzerland, it is likely to provide only a very small capacity for CO_2 disposal.

Natural gas reservoirs: Exploration for oil and gas has been carried out in Switzerland since the mid-1950s, including 35 deep boreholes and over 8500 km of geophysical surveys. However, only one small gas field, situated at Entlebuch, Canton Lucerne, has ever produced gas commercially (74 Mm^3 of natural gas, volumetrically equivalent to 1.3 Mt CO_2). Unfortunately, the Entlebuch gas trap lies more than 5000 m below the surface, so the cost of refilling the liberated rock porosity with waste CO_2 would be extremely high. Today, exploration for gas is continuing throughout the entire Central Plateau and the Jura Chain. Despite this activity, no potential has been indicated in Switzerland so far for this approach to CO_2 disposal.

Saline aquifers: Thick aquifers containing water of various levels of salinity are found at several levels below the Swiss Central Plateau and the Jura Mountain Chain. Many of these aquifers are well known to local hydro geologists and geothermal energy firms, and a certain amount of geological information is available from boreholes and geophysical transects. Whereas most of the aquifers lie buried deep beneath the surface, in some places of northern Switzerland the rocks are exposed in surface outcrops, thanks to uplift caused by tectonic activity in the distant past. Overall, these sources of information are sufficient to reconstruct approximately the three-dimensional disposition and thickness of the aquifers down to several kilometres depth. Hydraulic testing in boreholes and in the laboratory using core samples has provided quantitative information on the intrinsic porosity and permeability of the rocks. The thick sequence of sedimentary rocks underlying the Swiss Molasse Basin and the adjacent Jura Chain contains numerous sealed aquifers that are worth evaluating for CO_2 disposal. The aquifer rocks have measured porosities between 0.5 and 22%.

The conclusion of the BFE study was, therefore, that saline aquifers are the most promising option for CO_2 disposal in Switzerland.

However, according to the BFE [2.55], the literature data on the promising saline aquifers are, unfortunately, insufficient to quantitatively evaluate all of the geological criteria. Certain parameters are lacking completely, whereas data related to many of the criteria are too sparse to provide a meaningful basis for a three-dimensional evaluation. This state of affairs simply reflects the low areal density of deep boreholes in northern Switzerland and the lack of detailed hydraulic testing within these holes.

In view of the lack of reliable data, the assessment was based on a subset of the criteria and on data that are, at best, semi-quantitative. Criteria concerning seismicity and stress regime of the aquifer rocks are particularly important in view of the high population density of northern Switzerland, so not all the criteria carry the same weight in site selection. A numerical approach was, therefore, applied by which scores were assigned to the various attributes of the criteria, and the criteria themselves were weighted to enable their combination into a global estimate of disposal potential. The resulting numerical scale for CO_2 disposal potential ranges from 0 (negligible potential) to 1 (high potential). However, two features regarding the potentials must be kept in mind: first, although the use of numerical values may convey the impression of high accuracy, the results are based on qualitative and semi-quantitative data. Therefore, the numbers cannot have more than qualitative or at best semi-quantitative significance. Second, a high potential is not a guarantee that CO_2 can be disposed of in a given area. Rather, a high potential is simply a guide for exploration companies – an indication of an area that warrants further geological investigations.

Disposal capacities are only meaningfully calculated for aquifers that have at least moderately good potential, such that capacities were calculated for potentials greater than 0.6. This gave a sum of all the effective disposal capacities of 2680 Mt CO_2.

The calculated disposal capacities can be put into the local context by considering that the current annual emission of CO_2 from industrial sources in Switzerland is approximately 11.3 Mt (Table 2.11). The projected emissions are just a tiny fraction (~0.5%) of the potential disposal capacity of aquifers beneath the Central Plateau, as estimated with the semi-quantitative approach in this study. However, it is worth reiterating, here, that the disposal estimates are merely potential values. So far, no disposal capacity has been proven within Switzerland.

TABLE 2.11. SEALED AQUIFERS (IN STRATIGRAPHIC ORDER) BENEATH THE CENTRAL PLATEAU AND JURA CHAIN OF RELEVANCE FOR CO_2 DISPOSAL. SOURCE: [2.55].

Aquifer / *Sealing caprock*		Extent of sealed aquifer	Aquifer porosity
1	Upper Marine Molasses (OMM) sandstones / *Upper Freshwater Molasses (OSM) marls*	Regionally extensive, but only a small zone within 800–2500 m depth interval.	5–20%
2	Upper Malm – Lower Cretaceous limestones / *Lower Freshwater Molasses (USM) marls*	Regionally extensive below Central Plateau.	0.5–10%
3	Hauptrogenstein limestone / *Effingen Member calcareous mudstone*	Subregional extent below north-west Central Plateau.	≤ 16%
4	Sandsteinkeuper, Arietenkalk limestone / *Lias, Opalinus Clay*	Local scale aquifers. Volumes are difficult to estimate.	5–15%
5	Upper Muschelkalk / *Gipskeuper evaporites*	Regionally extensive below Central Plateau.	2–22%
6	Buntsandstein and fractured crystalline (non-sedimentary) basement / *Anhydrite Group evaporites*	Subregional extent below north-west Central Plateau. Sporadically underlain by water conducting fractured basement (volumes are difficult to estimate).	3–18%
7	Permo-Carboniferous trough sandstones / *Permian shales or Anhydrite Group evaporites*	Location and number of troughs and their sandstones are poorly known. Data are insufficient to estimate aquifer extents and volumes.	3–12%

Radioactive waste disposal

The proposed final disposal facility for ILW, HLW and SF is a series of horizontal emplacement tunnels located at a depth of approximately 650 m in the centre of an Opalinus Clay formation. The Opalinus Clay was deposited some 180 million years ago by the sedimentation of fine clay, quartz and carbonate particles in a shallow marine environment. It is part of a thick sequence of Mesozoic and Tertiary sediments in the Molasse Basin, which runs from the north-east to the west of Switzerland and through the potential sites identified for SF and HLW. There are several reasons for choosing the Opalinus Clay as the host rock for a repository for long lived wastes:

- The geochemical environment is expected to be stable over several million years;
- The reducing, slightly alkaline and moderately saline environment favours the preservation of the engineered barriers and radionuclide retention;
- In case radionuclides escape into water, they would be diluted and dispersed in the layers of chalk above and below;
- The Opalinus Clay has a self sealing capacity which reduces the effects of fractures. It also allows small and unlined, or large and lined tunnels to be built at several hundred meters depth;
- The sediments overlying the basement in this region, and the basement rocks themselves, are not considered to have any significant natural resource potential.

In combination, these features indicate excellent isolation potential for a repository within the Opalinus Clay. Additionally, the so called confining units will also contribute to radionuclide retention. There is also the likelihood of significant dilution of any such releases in groundwater in the permeable formations above and below the confining units before they reach surface aquifers in the biosphere, where further dilution takes place. The Opalinus Clay is of uniform thickness over several kilometres, almost flat lying (dipping gently to the south-east) and little affected by faulting.

The geological component of the isolation concept is, therefore, as follows:

- The absence of significant advective groundwater flow in the host formation, which is thick enough to extend for more than 40 m above and below a repository, will ensure that the rate of movement of radionuclides out of the engineered barriers and through the undisturbed host rock will be extremely small;
- The surrounding clay rich sediments are rocks of the confining units and have the additional potential to retard the movement of any radionuclides that escape from the host rock. Although there are thin and more permeable horizons in these clays, flows are expected to be small, due to limited hydraulic interconnectedness. Potential pathways to the biosphere are long (15–25 km, if they exist). Furthermore, the surrounding formations have good sorption properties;
- Any radionuclides that migrate through the clay rich formations (i.e. are not transported laterally along the thin, water conducting horizons), will enter the regional aquifers of the Malm (above) and the Muschelkalk (below). Neither of these aquifers or permeable horizons are exploited in this region, and, with the exception of the Muschelkalk, the waters have relatively high salinities and are non-potable. The current discharge area for Muschelkalk aquifer is some 30 km to the west, with the Malm discharging a few km to the north;
- If radionuclides enter the regional aquifers, they will be significantly dispersed and diluted. An additional stage of dilution will occur when the deep aquifers discharge to the more dynamic freshwater flow systems of near surface gravel aquifers, or to river waters. Groundwater directly discharging to springs is also being considered.

2.3.7.2. *Brief comparison of disposal options for CO_2 and radioactive waste*

It can be seen from the case study for Switzerland that some overlap does occur in the geographical regions determined to be of most interest to the disposal of radioactive waste and CO_2, particularly in the Zürcher Weinland region to the south of Schaffhausen. For radioactive waste, the selected clay rich formations must be thick enough (~100 m) to ensure long term impermeability with respect to formation water from above and below the repository. In effect, the combination of this depth constraint and the need for more than 30 m of impermeable rock beneath the repository rule out a geological conflict with CO_2 injection into an underlying saline aquifer.

Two of the formations being investigated for the disposal of radioactive waste were also considered to be potential sealing caprocks in the 2010 BFE study [2.55]: the Opalinus Clay and the Effingen Member. Owing to the slight south-east dip of these formations, most of the areas of interest for radioactive waste disposal lie to the north of and at shallower depths than the areas identified to have potential for CO_2 disposal.

2.4. CONCLUSIONS

Information on the geological potential of CO_2 disposal and radioactive waste disposal is presented in this chapter for Bulgaria, Cuba, the Czech Republic, Germany, India, the Republic of Korea and Switzerland. Data of CO_2 point sources are highlighted and possible geological disposal locations (aquifers, oil and gas fields, coal fields) are shown. Based on the references, the estimated geological disposal capacity gives several decades or even hundreds of years for all CO_2 emissions from the point sources. These estimates may be increased as further datasets become available in the different countries.

The results of this chapter can be summed up as follows:

- There are different requirements, depending on the geological environments in which CO_2 and radioactive waste would be disposed;
- There are obvious similarities between CO_2 disposal and radioactive waste disposal because both occur in geological media;
- The emplacement of radioactive waste and CO_2 in geological media is considered to be a safe method for isolating these substances from the accessible near surface biosphere;
- Some of the participating countries are investigating the development of a geological disposal facility for HLW;
- For CO_2 disposal, there is substantial experience available from the oil and gas industries specifically including EOR and EGR that is now being applied to develop this technology;
- In Bulgaria, there already exist two radioactive waste repositories, one of which (Novi Han) has been in operation since 1964, the other of which (Kozloduy) opened in May 2011. There are good geological conditions for CO_2 disposal;
- In Cuba, a near surface waste facility for LILW is at an early stage of planning. Currently, there are no plans for CO_2 disposal;

- In the Czech Republic, there are good geological conditions for the disposal of CO_2 and radioactive waste;
- In Germany, several options exist for the geological disposal of CO_2 and radioactive waste;
- India has very good and various geological conditions as well as high potential for CO_2 and radioactive waste disposal;
- The essential problem in the Republic of Korea is the long distance between the CO_2 emitting industries and the potential CO_2 disposal sites. The reduction of the transportation costs is the main task to increase the competitiveness of CCD projects;
- In Switzerland, there are six identified potential areas with suitable geological conditions for the disposal of radioactive waste. CO_2 disposal is not considered as an important issue for the country.

No direct conflict between the two disposal options has been revealed in any of the participating countries in terms of competition for geological space. This follows from the rather different characteristics of the geological formations suitable for disposing of CO_2 on the one hand, and radioactive waste on the other.

The chapter shows a considerable diversity of the perceived urgency to tackle the problems of geological disposal of CO_2 and radioactive waste across the participating countries. Accordingly, the intensity of and the resources mobilized for the necessary geological research vary a great deal. Research communities in the two areas greatly rely on the accumulated geological knowledge in their own fields, but this initial comparative analysis indicates that there are opportunities for the two expert groups to learn from each other. Approaches and processes of geological research reported in this chapter might be useful for other countries starting or intensifying geological research in these areas.

APPENDIX: FORMULAS

Capacity estimation in hydrocarbon fields

A simplified formula from the GESTCO project [2.56] can be used for estimates:

$$M_{CO2} = \rho_{CO2r} \times UR_p \times B$$

Where

M_{CO2}	is the hydrocarbon field disposal capacity;
ρ_{CO2r}	is the CO_2 density at reservoir conditions (the CO_2 density varies with depth as a function of pressure and temperature);
UR_p	is the proven ultimate recoverable oil or gas reserves;
B	is the oil or gas formation volume factor (for oil varies regionally depending on the oil type: a fixed value of 1.2 can be used for the oil replacement; for gas varies with depth as a function of pressure and temperature).

Capacity estimation in deep saline aquifers

The formula is slightly simplified and/or modified versions of the formulas presented in Bachu et al. [2.57]. It is the same for aquifer traps and regional aquifers:

$$M_{CO2t} = A \times h_{ef} \times \phi \times \rho_{CO2r} \times S_{eff}$$

Where

M_{CO2t}	is the 'trap' disposal capacity;
A	is the area of aquifer in trap (determined by contour maps of stratigraphic horizons near or at the top of the reservoir formation);
h_{ef}	is the average effective thickness of aquifer (evaluated by data from exploration wells);
ϕ	is the average reservoir porosity of aquifer (evaluated by data from exploration wells);
ρ_{CO2r}	is the CO_2 density at reservoir conditions (varies with depth as a function of pressure and temperature and can be estimated using different diagrams);
S_{eff}	is the disposal efficiency factor (for trap volume can be assumed between 5–10% for the different aquifers).

Capacity estimation in coal fields

The assessment methodology is based on the use of GESTCO reports on CO_2 ECBMR potential for Belgium [2.56], Germany [2.58] and the Netherlands [2.59].

The CO_2 disposal capacity in coal field(s) is a function of PGIP (producible gas in place), CO_2 (gas) density and CO_2 to CH_4 exchange ratio (ER):

$$S = PGIP \times CO_2 \text{ density} \times ER$$

CO_2 disposal capacity S denotes quantity of CO_2 that could replace PGIP, to the extent specified by *ER* (hard coal has usually the ratio of about 2, brown coal and lignite may have higher ratios)

PGIP means coal bed methane reserves for CO_2 ECBMR (Enhanced Coal Bed Methane Recovery with the use of CO_2 disposal). The standard approach to calculating *PGIP* consists of estimation of volume and mass of (pure) coal (excluding ash and moisture, if CH4 content refers to pure coal samples) within the seam(s), assuming methane content in coal, recovery factor and completion factor:

$$PGIP = \text{Coal Volume} \times \text{Coal density} \times CH_4 \text{ content} \times \text{Completion factor} \times \text{Recovery factor}$$

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Chapter 3

ENVIRONMENTAL IMPACTS

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3.1. INTRODUCTION

In consideration of the possible environmental impacts resulting from the disposal of radioactive waste and carbon dioxide (CO_2) in geological formations, there will be above ground disturbances to the land on which the surface infrastructures of the disposal facility will be sited, and which will lead to chains of resource uses and emissions from their construction and operation. For both waste types in question, the burdens on the environment from these processes can largely be measured in tens of years, and measures to reduce or limit them **can** be done in a reactionary and continuous manner. On the other hand, however, the disposal and containment of these wastes must, for the purposes of repository design, either be considered as potentially permanent in the case of radioactive waste, or ultimate in the case of CO_2. This means that, in practical terms, measures to control the environmental impacts during the decay or the mineralization processes, which continue long after above ground activities have ceased, can be done only once, prior to the emplacement of the waste in the geological formation.

Both natural and engineered barriers are incorporated into the disposal schemes with the ultimate objective of immobilizing the transport of radionuclides or CO_2 within the host geological formations, the duration of the necessary containment period being either until the waste has reached background radiation levels or the CO_2 has chemically bonded with the host rock. Thus, potential environmental impacts occurring here would be due to a release or transport of radionuclides or CO_2 into the surrounding geology and water courses prior to the end of the containment period, which, as described, must be guarded against from the outset. Indeed, if the safe and effective containment of wastes cannot be assured, then the justification for the geological disposal is, in itself, highly questionable. Therefore, with regard to the below ground disposal phase and however long that must last, there are no burdens or consequences on the environment (of which we are aware) from the normal operation of a facility. Only under the analysis of failure scenarios would a consideration of potential environmental impacts be a justified and valuable assessment. Within the precincts of normal operation, however, the analysis is thus focused on the above ground activities, on the preparation of the disposal and containment locations (relevant for radioactive waste, which uses engineered barriers) and on the eventual sealing and closure of the facility. What occurs below ground is assumed to be the safe and complete containment of the waste substance.

The subtle concerns regarding environmental impacts the public has about, for example, CO_2 leakage on human health, ecosystems, terrestrial and the marine environments, etc., are not captured here. These aspects are discussed in West et al. [3.1]. This chapter focuses on the life cycle assessment (LCA) approach and its application to CO_2 and radioactive waste disposal.

3.2. METHODOLOGIES

3.2.1. Life cycle assessment

The potential environmental impacts of radioactive waste disposal and CO_2 disposal are quantified by LCA methodology, taking into account not only direct burdens during construction and operation of disposal facilities, but also indirect burdens through energy and material demands. The results are valid for 'normal operation' of all processes included, meaning that the disposal facilities function as intended.

3.2.2. Basic principles of the LCA

LCA quantifies the environmental burdens of a certain product or service over its whole life cycle, beginning with the extraction of resources and covering the intermediary processing stages, the use phase, as well as final disposal. It includes fossil and mineral resource consumptions, land uses and emissions to air, water and soil.

The International Organization for Standardization has specified international guidelines on LCA [3.2]. Four main steps are distinguished: goal and scope definition, inventory assessment, impact assessment and interpretation (Fig. 3.1). Due to the comprehensive approach and the interdependent assessment steps, conducting a LCA is usually an iterative process.

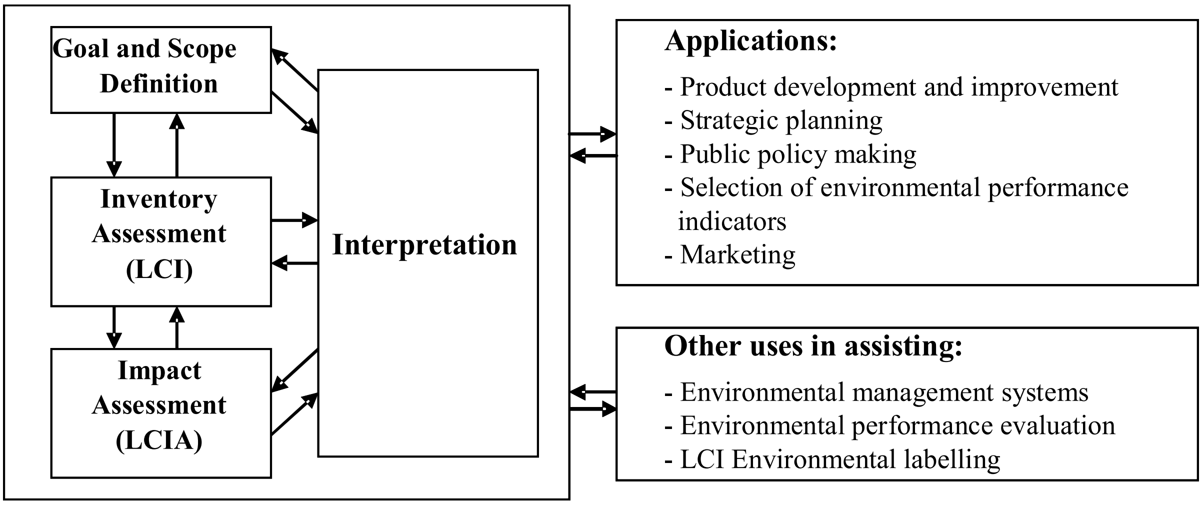

FIG. 3.1. Main steps and applications of the LCA.

The goal and scope define the fundamental characteristics and constraints of the LCA being conducted. Although the definitions of these aspects can also be iterated upon throughout the duration of a study, they provide a framework and guidelines for the collection of the inventory data. The LCI analysis quantifies all elementary flows associated with single processes, i.e. mass (materials and resources) and energy flows, land use, emissions to air, water and soil and products of the processes as outputs. The Life Cycle Impact Assessment (LCIA) is the third step within a LCA and focuses on the aggregation of specific or total environmental burdens. The concept of category indicators for environmental impacts is the basis for the LCIA. Each category has its own environmental mechanism, such as infrared radiative forcing for climate change or proton release for those leading to acidification. All mass flows taken into account in the LCI are classified and multiplied with specific characterization factors concerning the specific environmental burden for a specific impact category. Finally, the results obtained must be interpreted within the contextual setting of the study. If an adequate interpretation cannot be made, then aspects of the previous stages should be altered in order to achieve it.

The LCIA also contains optional elements such as normalization and weighting of the burdens and impacts, respectively [3.3]. Normalization allows for the comparison of different category indicators by dividing the values with a selected reference value, such as total emissions or resource uses for a certain area (such as the whole of Europe), in order to determine a potential impact. Weighting indicators allows for a differentiated rating of impacts where the weighting factors depend on personal value judgments and not only on scientific criteria. Due to the strong element of subjectivity involved in this, different weighting schemes, as well as sensitivity analysis, may be helpful for the consolidation of results and conclusions. The LCIA can also be used to analyse the contributions from system parts or for use in product optimization.

3.2.2.1. Database, data collection and software

The LCA performed here uses background data from the ecoinvent LCI database [3.3]. The ecoinvent LCA database contains more than 4,000 individual processes covering the whole economic system with a focus on European production chains. For important globally traded goods (e.g. energy carriers like oil, gas, coal and uranium), regions outside of Europe are also considered. These LCI data mainly refer to conditions existing around the years 2000–2005.

Additional data specific to the comparison of the disposal of radioactive waste and CO_2 are taken from various studies conducted at the Paul Scherrer Institute. These were also done in conjunction with the methodologies and guidelines of the ecoinvent database and could, therefore, be used in the present study with a high degree of consistency. The construction of specific inventories and processes determined for this chapter was done using the SimaPro software [3.4]. With this software, a number of indicators and impact assessment methodologies are available, which allow an iterative procedure between results and inventory data.

3.2.2.2. Functional unit

Cumulative LCA results are given in quantity of emissions per unit of electricity from a power plant or a mix of power plants generating the flow of radioactive waste or CO_2 requiring geological disposal, i.e. kg CO_2-eq/MW·h. Results could, of course, be given for the functional unit of 1 kg radioactive waste or CO_2, but these are not the useful products of the systems of which they are a part. Instead, in order to generate 1 MW·h electricity, a given quantity of radioactive waste or CO_2 is produced and requires disposal, and this volume or weight is different per unit of electricity generated. Therefore, although the focus of the study is on radioactive waste and CO_2 disposal, a comparison of environmental impacts should not remove them from the context of why they are being produced.

3.2.2.3. Indicators and impact assessment methods

This chapter uses a combination of assessment methods in order to evaluate the environmental burdens and potential impacts of radioactive waste and CO_2 disposal (see Table 3.1). The first sections address specific cumulative inventory results, characterized according to equivalency factors to suit their particular burden on the environment. For the analysis and interpretation of the cumulative life cycle inventories, this chapter uses selected methods as implemented in the ecoinvent database [3.5]. These address the specific impacts of climate change, as well as selected pollutants.

TABLE 3.1. INDICATORS AND ASSESSMENT METHODS USED IN LCA

Indicator	Units	Description	Main substances
Greenhouse gas (GHG) emissions	g (CO_2-eq)	The global warming potentials (GWP) of GHG are calculated using the CO_2-equivalent GWP factors for a 100 year time period, determined by the IPCC [3.6].	*CO_2, methane, dinitrogen monoxide, fluoro-chlorohydrocarbons.*
Acidification and eutrophication	PDF*m^2*year	Quantification of the potentially disappeared fraction (PDF) of flora and fauna species per unit area and time, due to emissions which alter natural pH and nutrient levels [3.7].	*Ammonia, nitrous oxides and sulphur oxides.*
Ecotoxicity	PAF*m^2*year	Quantification of the potentially affected fraction (PAF) of flora and fauna species per unit area and time, due to toxic emissions [3.7].	*Heavy metals, dioxins and hydrocarbons.*
Respiratory inorganics	DALY	Quantification of potential impacts on human health using the Disability Adjusted Life Year (DALY), which combines premature mortality and years of life lost caused by airborne pollutants [3.7].	Particulate matter, ammonia, nitrous oxides and sulphur oxides.

3.3. COUNTRY CASE STUDIES

3.3.1. Radioactive waste disposal

Within the scope of this chapter, it was not feasible to collect suitable and methodologically consistent LCI data from each country participating in the overall assessment to conduct a LCA and to develop inventories with which to calculate environmental burdens and impacts. However, even though most country specific radioactive waste disposal strategies are still in the design phase, a consensus has emerged amongst the leading technical authorities that disposal in deep underground facilities presents the best current and foreseen solution. For the most part, the repositories are expected to be located at depths of less than 1000 m and comprise a series of engineered emplacement shafts [3.8]. It can, therefore, be assumed that the design characteristics, materials and energy sources used to construct and operate each facility will not differ significantly with regard to the results of an environmental impact assessment. For the reasons explained in the introduction, the environmental burdens considered in this chapter are limited to land and resource uses and the emissions occurring above ground. It is also important to bear in mind when considering such a LCA that the disposal is just one aspect in a whole life cycle chain with the ultimate purpose of generating electricity (Fig. 3.2). As the following analysis shows, other stages in this overall chain are far more significant in terms of environmental burdens than the disposal of wastes. This also means that the functional unit (the product of the system to which all burdens and potential impacts are related) is 1 kW·h electricity at the busbar of the nuclear power plant (NPP).

Therefore, and considering the above arguments, the following analysis of radioactive waste disposal will be limited to the LCA case study of radioactive waste disposal in Switzerland, for which LCIs already exist [3.9].

3.3.1.1. System boundary of the nuclear energy chain

The system boundary of the complete life cycle of electricity production from western European NPPs (e.g. France, Germany and Switzerland) is represented in the ecoinvent database [3.9]. Figure 3.2 shows the main processes of uranium mining and processing to fuel elements, the construction and operation of the NPP, reprocessing and conditioning of used fuel and the final disposal of radioactive waste.

3.3.1.2. System boundary of radioactive waste disposal

The system boundary of the radioactive waste disposal stage encompasses the above and below ground infrastructures and emplacement of the wastes in geological repositories. Interim waste storage and transport of the waste to the above ground facility is not included. Radioactive waste is disposed of in two repositories: one for spent fuel (SF), high level waste (HLW) and long lived intermediate level waste (ILW), and one for short lived ILW and low level waste (LLW). All forms of waste are quantified in terms of volume occupied within the repository, which includes all the containment and encapsulation material with which the radioactive waste was conditioned and packaged for final disposal.

3.3.1.3. Life cycle assessment case study of radioactive waste disposal in Switzerland

If the five Swiss reactors are assumed to operate for 60 years each, then this would be the equivalent of 192 GW·year of electricity, resulting in approximately 16 000 m^3 of conditioned SF and HLW [3.10]. More specifically, this would be composed of approximately 8000 m^3 of SF, 1000 m^3 of HLW and 7000 m^3 of ILW. For LLW and ILW, the repository would be designed to accommodate 75 000 m^3 of waste (conditioned and packaged). The repository would be operational for approximately 50 years [3.10]. These volumes equate to 8.6×10^{-9} m^3 of SF, HLW and ILW and 4.7×10^{-8} m^3 of LLW on a per kW·h basis. The nuclear power mix in Switzerland is defined as being 55% from pressurized water reactors (PWR) and 45% from boiling water reactors (BWR) [3.9].

The environmental burdens and potential impacts are shown in Fig. 3.3. For each indicator, the contribution from radioactive waste disposal is differentiated from the rest of the life cycle chain of electricity generation. In each case, SF and HLW account for between 60% and 70% of this contribution.

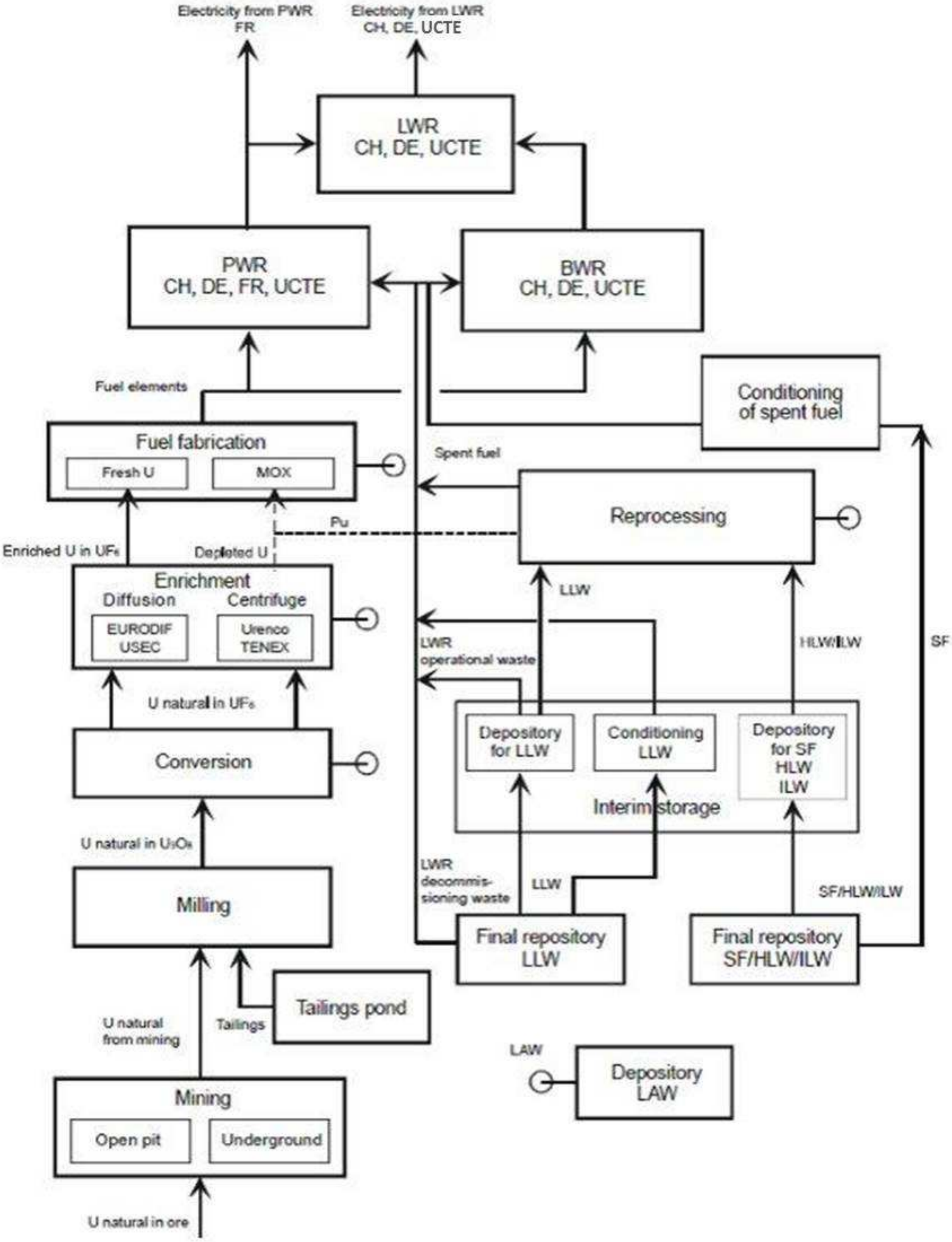

FIG. 3.2. System boundary of the nuclear energy chain, as modelled in the ecoinvent database [3.9]. Note: UCTE – Union for the Co-ordination of the Transmission of Electricity.

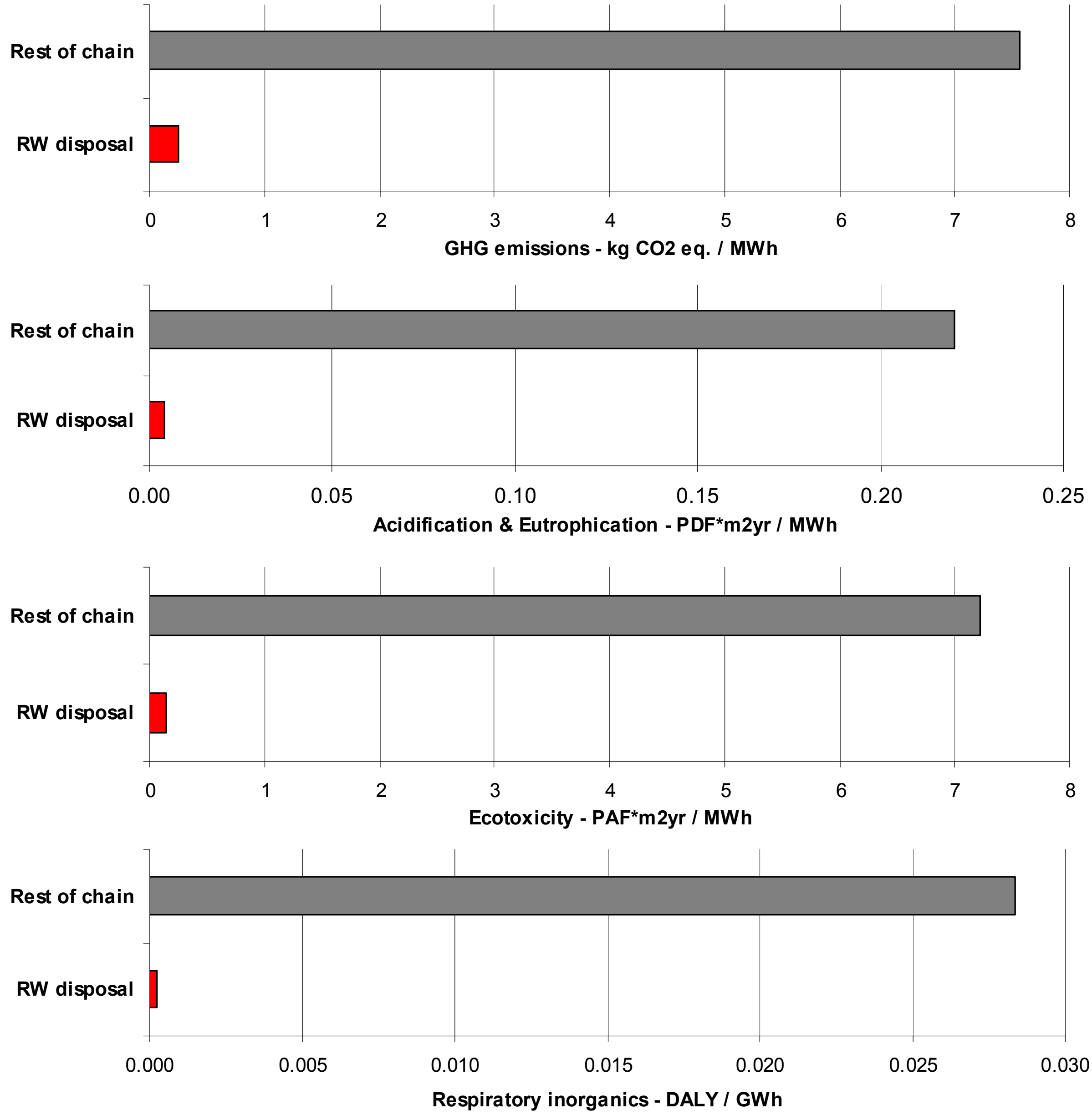

FIG. 3.3. LCIA results for electricity production from nuclear power in Switzerland. Results are given per unit of electricity generated and differentiated between radioactive waste disposal and the rest of the life cycle chain. Source [3.9].

Note: RW=radioactive waste

3.3.2. CO_2 disposal

3.3.2.1. System boundary of the fossil energy chain

Fig. 3.4 shows the simplified system boundary of the complete life cycle of electricity production from fossil fuel power plants with carbon capture and disposal (CCD) technology (either natural gas or lignite, both with post-combustion capture), as modelled by Volkart [3.11]. This figure shows the main processes of fossil fuel extraction and processing, the construction and operation of the power plants and the different stages of the CCD process.

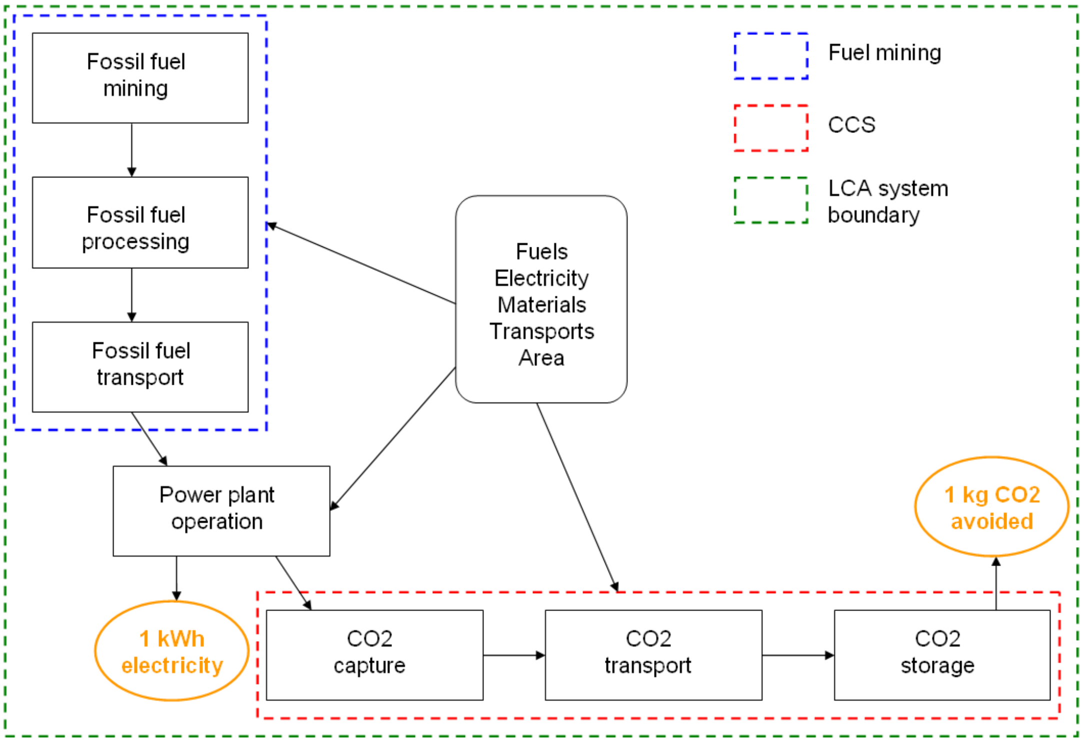

FIG. 3.4. System boundary of the fossil fuel energy chain with CCD, as modelled by Volkart [3.11].

3.3.2.2. System boundary of geological CO_2 disposal

CO_2 arrives at the injection site in supercritical form, meaning that it is compressed to around 8 Megapascal (MPa) (80 bar) pressure and in liquid state. Similarly to radioactive waste, the disposal site forms the system boundary of the evaluations so that the transport of the CO_2 to the injection site is not considered. Additional pressurization according to the depth of the host formation is, then, a site specific variable and, as such, very much a part of the LCA. Furthermore, as this happens at the injection site, not only the quantity used but also the form and source of the energy used to enable CO_2 injection has a significant influence on the LCA results. For the cases studied below, the additional pressure at the injection sites is gained using electric compressors powered by the country specific electricity supply mix.

3.3.2.3. LCA case study of CO_2 disposal in Switzerland

CO_2 is assumed to originate in a gas turbine combined cycle plant (GTCC) using post-combustion carbon capture. The gas turbine combined cycle plant has a capacity of 400 MW(e) and a CO_2 capture rate of 90% [3.12], equivalent to 0.36 kg CO_2 per kW·h of electricity exported to the grid, or approximately 39.5 kg CO_2/s. For the Swiss case, CO_2 is assumed to be stored in a saline aquifer 1000 m below ground level [3.13]. The pressure of the CO_2 is increased to approximately 200 bar [3.11] and uses medium voltage electricity from the Swiss supply mix. The results of the LCIA can be seen in Fig. 3.5.

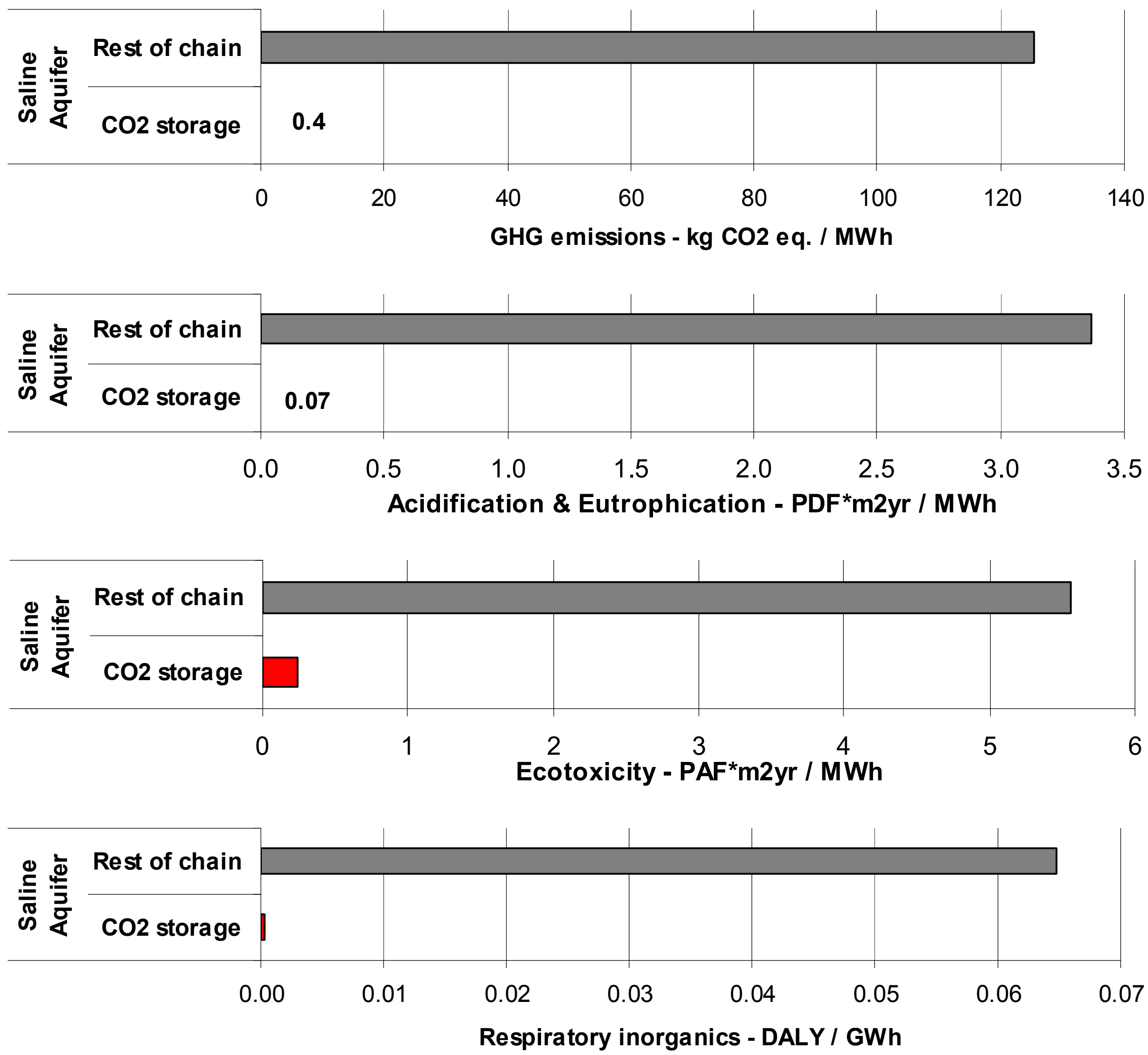

FIG. 3.5. LCIA results for electricity production with CCD in Switzerland. Results are given per unit of electricity generated and differentiated between the CO_2 disposal and the rest of the life cycle chain. Sources: [3.9], [3.10], [3.11].

3.3.3. LCA case study of CO_2 disposal in Germany

CO_2 is assumed to originate from the combustion of lignite in an integrated gasification combined cycle (IGCC) plant using post-combustion carbon capture. The IGCC plant has a capacity of 450 MW(e) and a CO_2 capture rate of 90% [3.12], equivalent to 0.934 kg CO_2 per kW·h of electricity exported to the grid or approximately 117 kg CO_2/s. For the German case, two disposal scenarios are assessed based on reference [3.11] (see Fig. 3.6). The first is a saline aquifer of 1000 m depth and permeability of 500 to 1000 mD (millidarcy), requiring an injection pressure of almost 180 bar and, therefore, additional compression at the injection site of 10 MPa (100 bar). The second is a depleted gas field 3300 m below the surface with permeability of 10 to 100 mD. These factors mean that disposal in the latter requires a much higher injection pressure of around 420 bar (compression from 8 to 42 MPa, or 80 to 420 bar, at the injection site).

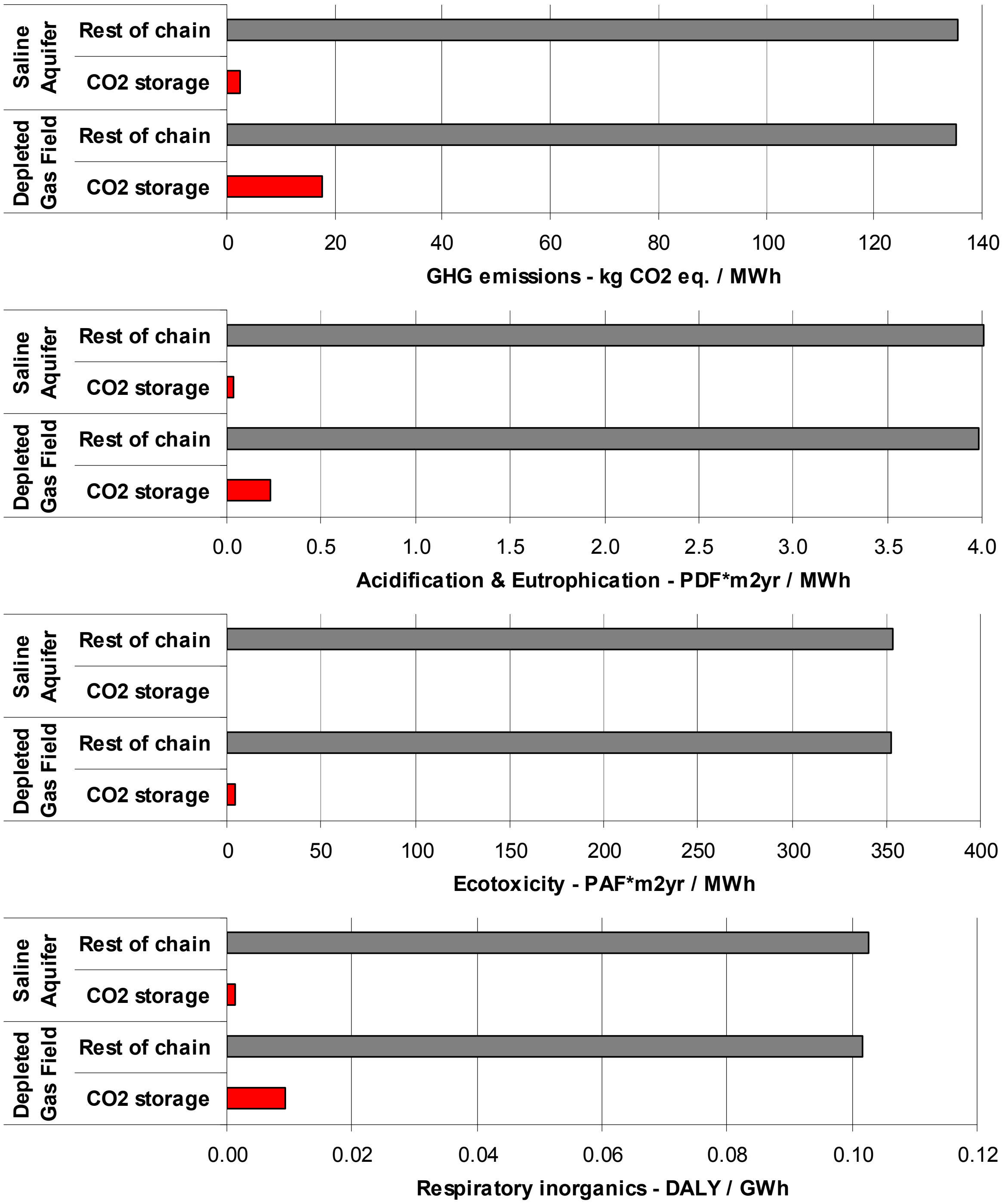

FIG. 3.6. LCIA results for electricity production with CCD in Germany. Results are given per unit of electricity generated and differentiated between the CO_2 disposal and the rest of the life cycle chain for a saline aquifer and a depleted natural gas field. Sources: [3.9], [3.10], [3.11].

3.3.4. Country specific conclusions

3.3.4.1. Switzerland

For Switzerland, it was possible to determine potential environmental burdens and impacts of the geological disposal of both radioactive waste and CO_2. Site location, engineered barriers and design concepts of radioactive waste repositories have been extensively researched and developed, due to the implicit need for this kind of facility. On the other hand, the relatively small contribution of fossil fuels to the Swiss electricity mix has meant that the research and development commitment to CCD is only recently being approached as Switzerland considers potential future generation possibilities.

Based on the indicators used, the results show that the potential environmental burdens and impacts from radioactive waste disposal form only a very small fraction of the cumulative burdens and impacts from the complete life cycle of generating electricity at a NPP). As can be seen in Table 3.2, this fraction is, at most, a little more than 3% in the case of GHG emissions. The results given in this table are per unit of electricity generated and differentiated between the radioactive waste disposal and the rest of the life cycle chain [3.9].

For CO_2 disposal, the data has been generated through scenario analyses and similar or analogous processes outside of Switzerland. This analysis also shows that the specific stage of CO_2 injection into the geological formation (saline aquifer) accounts for only a small fraction of the overall cumulative burdens and impacts, being, at most, just over 4% in the case of ecotoxicity. Here, the contributions largely stem from the electricity sources constituting the Swiss electricity mix. Table 3.3 shows the results of LCIA for electricity production in Switzerland with CCD. Results are given per unit of electricity generated and differentiated between the CO_2 disposal and the rest of the life cycle chain [3.9], [3.10], [3.11].

TABLE 3.2. LIFE CYCLE IMPACT ASSESSMENT RESULTS FOR ELECTRICITY PRODUCTION FROM NUCLEAR POWER IN SWITZERLAND

Swiss nuclear mix	GHG emissions kg CO_2-eq / MW·h	Acidification and eutrophication PDF*m^2*year / MW·h	Ecotoxicity PAF*m^2*year / MW·h	Respiratory inorganics DALY/GW·h
Rest of chain	7.56	0.22	7.22	0.0284
Radioactive waste disposal	0.25	0.00434	0.148	0.000236
Total	7.81	0.224	7.37	0.0286
Radioactive waste disposal as % of total	3.20%	1.94%	2.00%	2.74%

TABLE 3.3. LIFE CYCLE IMPACT ASSESSMENT RESULTS FOR ELECTRICITY PRODUCTION WITH CCD IN SWITZERLAND

Disposal in saline aquifer	GHG emissions kg CO_2-eq/ MW·h	Acidification and eutrophication PDF*m^2*year/ MW·h	Ecotoxicity PAF*m^2*year / MW·h	Respiratory inorganics DALY/GW·h
Rest of chain	126	3.36	5.55	0.0648
CO_2 disposal	0.442	0.0071	0.246	0.000318
Total	126	3.37	5.80	0.0651
Disposal as % of total	0.35%	0.21%	4.23%	0.49%

3.3.4.2. *Germany*

For Germany, it was possible to generate LCA results for different CO_2 disposal scenarios, as well as cumulative for the rest of the energy chain in electricity production. The two disposal scenarios are a saline aquifer (as for Switzerland) and a depleted gas field, and the use of these highlighted the possibility for the injection stage to vary significantly in its level of contribution to the cumulative burdens and impacts per unit of electricity. This was most predominant for GHG emissions where the contribution varied from almost only 2% in the case of the saline aquifer to more than 11% in the case of the depleted gas field. Injection is an energy intensive process, due to the need to compress the CO_2 above the level of that which arrives at the injection site in the pipeline. In the case of the depleted gas field, the further increase in pressure above the pressure in the pipeline is more than three times that for the saline aquifer (36 MPa as opposed to 10 MPa). Compression is performed by using an electric compressor fed by the Union for the Co-ordination of the Transmission of Electricity (UCTE) electricity mix representative of 2005. Table 3.4 shows LCIA results for electricity production with CCD in Germany. Results are given per unit of electricity generated and differentiated between the CO_2 disposal and the rest of the life cycle chain. Two disposal scenarios of saline aquifer and depleted natural gas field are presented [3.9], [3.10], [3.11].

TABLE 3.4. LIFE CYCLE IMPACT ASSESSMENT RESULTS FOR ELECTRICITY PRODUCTION IN GERMANY

Disposal in saline aquifer	GHG emissions kg CO_2-eq/MW·h	Acidification and eutrophication PDF*m^{2}year/MW·h	Ecotoxicity PAF*m^2*year/MW·h	Respiratory inorganics DALY/GW·h
Rest of chain	135	4.01	353	0.103
CO_2 disposal	2.54	0.0343	0.709	0.00137
Total	138	4.04	354	0.104
Disposal as % of total	1.84%	0.85%	0.20%	1.32%
Disposal in depleted gas field				
Rest of chain	135	3.98	352	0.102
CO_2 disposal	17.8	0.235	4.64	0.00934
Total	153	4.22	357	0.111
Disposal as % of total	11.60%	5.57%	1.30%	8.42%

3.4. COMPARATIVE ASSESSMENT

Whilst maintaining the context of complete energy chains, the comparison of the results for just the radioactive waste and CO_2 disposal stages allows the contributing factors, which are illustrated in Tables 3.2 and 3.3, to be shown relative to each other and across countries. In Fig. 3.7, radioactive waste disposal is shown to cause the lowest environmental burdens, showing, overall, around half the amount of burdens caused by CO_2 disposal in a saline aquifer in Switzerland. The burdens from radioactive waste disposal are spread across several factors, such as energy uses and materials processing, whereas for CO_2 disposal, the main contributing factor is the energy source and energy demand for the compression of CO_2 at the point of injection. Here, the fossil fuel intensity of the electricity mix available in Germany and the higher pressure required cause the burdens and impacts to be many times larger than for CO_2 in Switzerland, or for radioactive waste disposal, in general. Table 3.5 shows the details of the electricity mixes used for CO_2 disposal, as well as their GHG emission intensities.

TABLE 3.5. PRIMARY ENERGY SOURCES AND GREENHOUSE GAS INTENSITY OF THE SWISS AND UCTE ELECTRICITY MIXES. Source: [3.14]

	Nuclear	*Fossil*	*Hydro*	*Others*	*GHG intensity*
Switzerland (based on 2005)	49.3%	8.1%	35.4%	7.2%	*140 g CO_2-eq / kW·h*
UCTE (based on 2005)	*31.6%*	*51.2%*	*11.4%*	*5.8%*	*590 g CO_2-eq / kW·h*

Note: UCTE – Union for the Co-ordination of the Transmission of Electricity

3.5. CONCLUSIONS

This chapter has focused on specific stages in the life cycle of electricity generation which are not yet practiced on industrial scales in any of the countries participating in this Coordinated Research Project. As a consequence, and despite applying up to date findings from the literature and from first experiences in other countries, the results inherently contain some degree of uncertainty. The LCA is a key tool in the assessment of technology options, because it sheds light on both the up and downstream stages of a product life cycle, and, therefore, includes both direct and indirect contributions into an overall quantification of burdens and potential impacts of radioactive waste and CO_2 disposal. In the case studies presented in this chapter, the LCA has been critical to confirming the very low contribution of radioactive waste and CO_2 disposal strategies to the overall burdens and potential impacts of electricity generation via nuclear or fossil power plants.

For radioactive waste disposal, the factors contributing to the burdens and impacts are very diffuse, occurring in the use of fossil fuels, but also in the extraction and processing of materials, as well as from the overall distribution of energy. There are no individual stages that stand out as being dominant and where efforts could be focused in order to reduce the environmental consequences. For CO_2, on the other hand, the main contributions to the environmental burdens come from the energy sources used to generate electricity for powering compressors at the injection sites. Therefore, depending on the electricity mix and the demand per kg CO_2, the effect can be either negligible, as in the case of disposal in a shallow saline aquifer in Switzerland, or highly significant, as in the case of disposal in a deep depleted gas field in Germany. For the latter, a very high compression requirement and a fossil fuel intensive electricity mix leads to environmental burdens from this stage which can be 40 times that for the Swiss case and 70 times that of radioactive waste disposal. The results were determined based on a functional unit of 1 MW·h or 1 GW·h electricity from the power plant producing the radioactive waste or CO_2 for disposal.

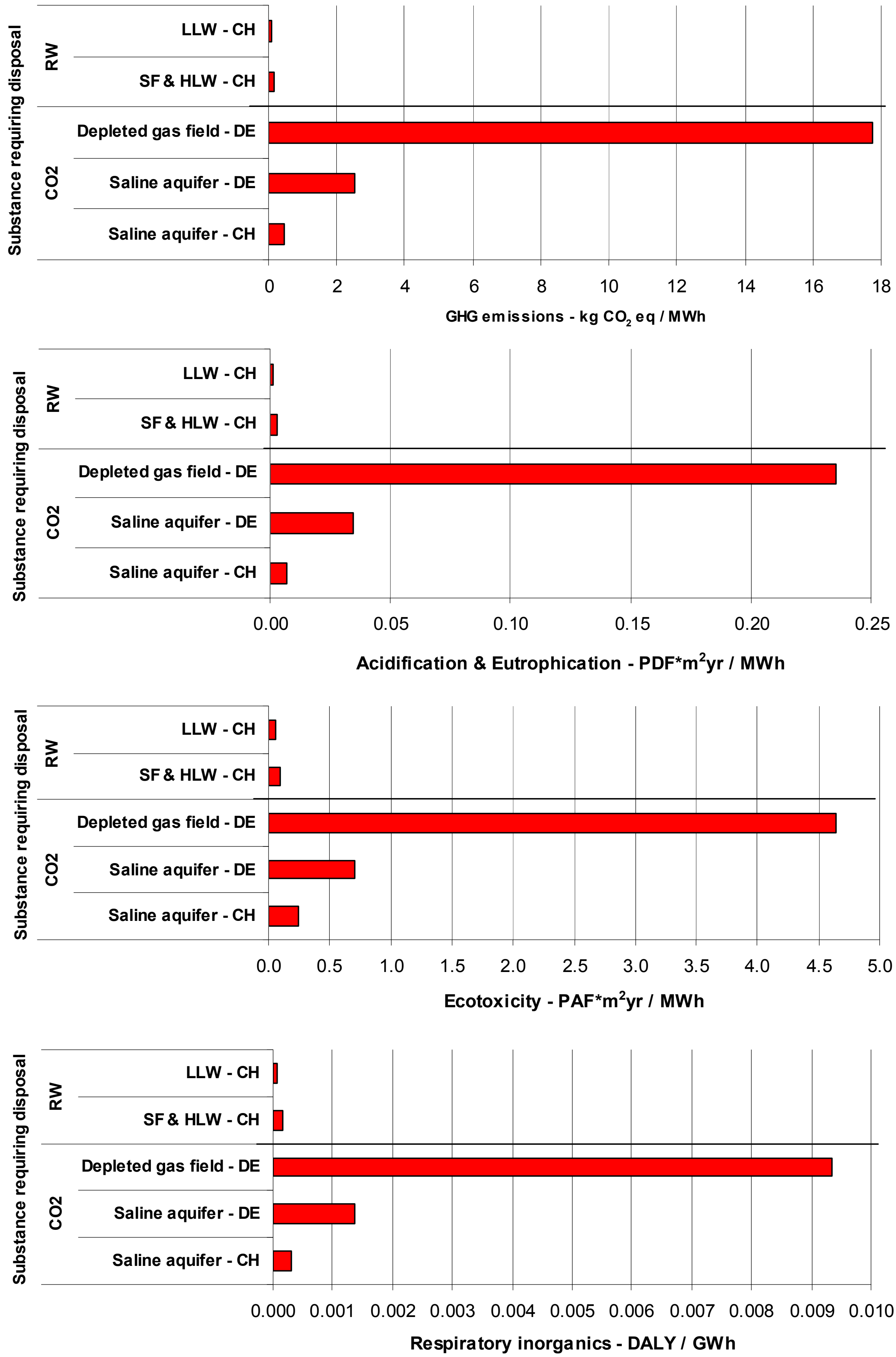

FIG. 3.7. LCIA results for the disposal of radioactive waste and CO_2 per unit of electricity generated from respective energy chains. Sources: [3.9], [3.11], [3.12], [3.13].
Note: CH – Switzerland, DE – Germany

The group of LCA researchers at the Paul Scherrer Institute is continually involved in improving and extending the body of LCI data modelling the disposal of radioactive waste and CO_2. Within the frameworks of current projects, this mainly focuses on Swiss case studies, but the wide applicability of the technologies assessed and the groups' awareness of the critical issues involved mean that data can be readily adjusted to suit different conditions.

The global energy sector is currently under considerable pressure to change its strategy and is exploring a very broad spectrum of technologies for electricity generation. In consideration of the advantages and disadvantages of each option, it is almost certain that nuclear and fossil power will continue to be significant sources of electricity for the coming decades on the global scale. The methods and examples presented in this chapter will be important elements of analysing their environmental performance of existing and future radioactive waste and the CO_2 produced.

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Chapter 4

SAFETY AND RISK ASSESSMENT

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4.1. INTRODUCTION

The disposal of waste/hazardous substances is an important issue concerning toxic substances, such as spent fuel (SF), high level waste (HLW) or carbon dioxide (CO_2). Radioactive waste disposal considers the long term emplacement of radioactive material until its activity and (radio)toxicity decreases below acceptable levels or until the species decay to the levels similar to those of natural uranium ore bodies. The main goal of CO_2 disposal in the geological environment is to contain large volumes of the gas in a safe and permanent way in order to avoid its release in the atmosphere. The main difference between CO_2 and radioactive waste disposal is the form of the matter to be disposed. While disposal considers the allocation of small amounts of highly radioactive and radiotoxic material, CO_2 disposal presumes the injection of large volumes of gas into rock structures.

The evaluation of safe disposal performance is an inevitable part of any such disposal programme. The geological disposal facility is considered safe if it meets the relevant safety standards that are internationally recommended and then defined by the national regulator [4.1]. Based on the waste character, all the possible effects and impacts on system behaviour/evolution have to be assessed in order to specify potential risks that might negatively influence members of the critical inhabitant group and biota. The system/subsystem behaviour and its performance during defined timescales have to be assessed and collated towards defined safety constraints. All the activities of either direct mitigation during the operational phase or passive system behaviour evaluation during the post-closure period should provide proof ensuring as low an impact on human and the environment as possible [4.2]. Such a declaration is usually a crucial requirement for licensing by responsible authorities.

The terms ‘risk’ and ‘safety’ sometimes mingle. Risk can be defined as a “*product of the probability that a specified hazard will cause harm, and the consequence of that harm”* [4.3]. Risk can also be defined as a product of the probability that some event will occur, and as the consequence of that event if it does occur [4.4]. Each site for geological disposal should be characterized for safety and integrity in the short and long term, including an assessment of the risk of leakage under the proposed conditions of use, and of the worst case impacts on the environment and human health [4.5], [4.6]. Furthermore, risk assessment can be defined as an assessment of the safety of a certain activity. Risk management is, then, the identification, assessment and prioritization of risks, followed by coordinated actions in order to monitor, minimize and control the probability and/or impacts of irregular events.

The goal of safety assessments is usually defined as an assessment of disposal system behaviour and its effect on safe performance of disposal facilities [4.2]. The safe performance of a deep geological disposal facility is usually evaluated for the post-closure period, where disposal system evolution depends mainly on environmental passive control. The results can also be presented as the risk, namely in relation with human health and the environment [4.3].

A safety assessment of a radioactive waste disposal facility can be also stated to be a systematic analysis of the hazards associated with geological disposal facility development and the ability of the site and designs to provide the safety functions and meet the technical requirements that are usually levels of individual dose and/or radiotoxicity. A safety assessment must identify and evaluate potential deviations from so called scenarios, i.e. evolution without important perturbations [4.7], [4.8], [4.9]. The results of the safety assessment are compared against criteria for safety and performance indicators (limits; see above) or, possibly, other performance measures or possible consequences of radionuclide release from the disposal system.

The periods considered for radioactive waste disposal safety assessments are long timescales of up to one million years, due to the presence of long lived radioisotopes. In most countries, national regulations directly establish a temporal limit [4.8], [4.9], [4.10], [4.11], [4.12]. Safety during the operational period is usually governed by radiation protection and health requirements, based on national legislations.

The evaluation of safe performance of CO_2 disposal has to be considered on two timescales: the short term timescale of up to several tens of years, when the effect on the global environment is considered in the event that CO_2 escapes into the atmosphere and hampers the main reason for disposal; and the longer term timescale, from a few hundreds of years up to several thousands of years [4.3], [4.6], [4.13]. [4.14]. If operational safety during CO_2 injection has to be taken into account, the local effects of CO_2 on humans and biota due to potential leakage must also be considered. The long term effects usually consider a gradual escape of CO_2, causing a local impact on health, safety and the environment in the injection region, being, however, mostly indirect.

The local extent of impacts of radioactive waste and CO_2 disposal during system evolution differ. Radioactive waste disposal usually considers local consequences, i.e. the migration of a limited amount of substances into the surrounding host rock environment and their transport towards the biosphere, with a possible influence on humans and the environment. Radioactive substances are usually considered to be trace contaminants that need not necessarily affect the surrounding environment. Therefore, only direct effects, due to radioactivity and radiotoxicity, are usually considered. The risk is usually related to the individual effective dose of critical inhabitant group members (Sv/year) or the individual risk (fatal cancer yearly risk) [4.1], [4.8]. The acceptable limits are usually strictly defined in national legislations.

CO_2 leakage can have two potential consequences: a local effect and a global effect. Local effects usually influence the local region close to the injection well. The large volumes of injected CO_2 can have either a direct impact on biota and humans as a suffocating gas, or an indirect effect, influencing, e.g. groundwater mass movement, potable water quality, etc. Furthermore, as mentioned above, escaping CO_2 could globally influence greenhouse gas levels, as their decrease has been the main goal of CO_2 disposal [4.13], [4.14], [4.15]. On the other hand, CO_2 can change the geological environment, due to either direct reactions (dissolution of host rock and caprock, biogeochemical reactions), or due to indirect influence (micro-seismic events, etc.). Life processes could also be influenced by altering physiological processes of micro- and macro-fauna, such as respiration, which will be important for subsurface and surface ecosystems. Additionally, injection can cause the mixing of saline water mass originating from the injection well area with other groundwater mass being used for domestic or potable purposes. Moreover, CO_2 could cause a release of elements harmful to health that might influence the quality of potable water.

CO_2 effect limits are defined according to the resulting impact. Limits for human exposure to CO_2 are usually defined by occupational health limits, e.g. permissible exposition limits (PEL) and the highest acceptable concentrations. The definition of CO_2 effects on the environment (e.g. animals, plants) is still not well established [4.16]. Limits for CO_2 concentrations in surface and subsurface waters are not used, as CO_2 is generally not considered as a harmful substance. The trace component (metal and toxic substances) content in potable water that might be influenced indirectly by CO_2 injection is usually defined in national legislations and health limits.

4.2. METHODOLOGY

Safety assessment methodology for radioactive waste disposal is presented in many IAEA and OECD NEA documents [4.1], [4.2], [4.8], [4.9], [4.10], [4.11], [4.12], [4.15], [4.17]. The first step of safety analyses comprises the assessment context specification. Furthermore, the disposal system must be characterized on the basis of field and lab research and natural analogue information. The following steps include scenarios formulation and justification, using, for example, a features, events and processes (FEP) list [4.10], safety functions for all system components, safety indicators, etc. The model for the consequence analyses then has to be formulated and implemented [4.8]. The interpretation of consequence analyses results and their comparison with assessment criteria results in the development of the safety case (see Fig. 4.1). The safety case can then be accepted or rejected, depending on the relevance and the degree of characterization. In any case, further measures must be taken afterwards. An example of a comprehensive approach can be found in [4.12]. The choice of safety assessment methodology is not simply based on the selection of a host rock formation. Most radioactive waste disposal programmes used the previously mentioned approach, modifying the procedure in order to develop a safety case. However, similar approaches have been chosen by the most of the implementing organizations all over Europe (e.g. France, Sweden, Finland, Switzerland, Belgium and France [4.12].

Compared to radioactive waste disposal, there are fewer international recommendations for CO_2 disposal risk/assessment methodology. The 2009 European Union (EU) Directive on the geological disposal of carbon dioxide [4.5] considers that the assumed behaviour of a CO_2 disposal site presumes that the rock environment provides permanent containment for the CO_2 stream as intended. This Directive assumes that the regulatory framework for geological disposal should be based on an “integrated risk assessment for CO_2 leakage, including site selection requirements, designed to minimise the risk of leakage, monitoring and reporting regimes to verify disposal and adequate remediation of any damage that may occur” [4.5]. Any potential deviation from the reference scenario should be identified and evaluated by detailed analyses.

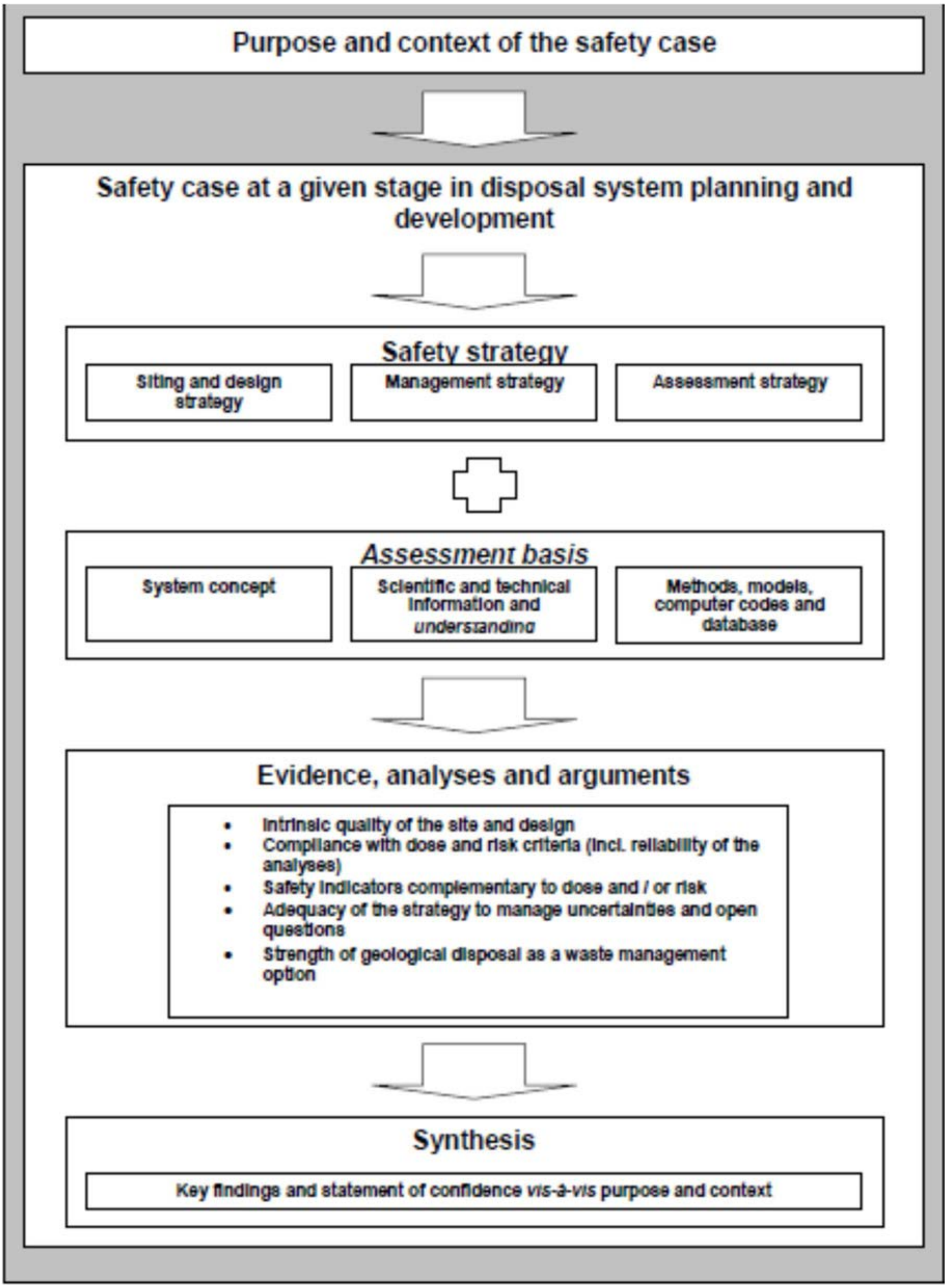

FIG. 4.1. Relation between different components of the safety case. Source: [4.10]

Safety/risk assessment methodologies for CO_2 disposal have recently developed rapidly [4.18], [4.19], [4.20], [4.21], [4.22], [4.23], [4.24], [4.25], [4.26]. In some cases, these procedures use similar schemes as those used in radioactive waste disposal (e.g. [4.6], [4.25], [4.26]) and implement some of the common features from the field of radioactive waste disposal (e.g. FEP list, scenario identification, scenario analyses, safety assessment modelling, what-if scenarios). However, the safety case, as one of the most effective approaches used in RW safety assessment, has not been used for this purpose in CO_2 disposal.

In contrast, some publications present differing approaches:

- A strictly mathematical approach for the determination of leakage risk [4.15];
- The Certified Framework (CF) method, based on the calculation of CO_2 Leakage Risk (CLR) for each compartment of the system. The Effective Trapping Threshold (ETT) has to be met for the site to be considered safe [4.17];
- The Vulnerability Evaluation Framework (VEF), which identifies a number of important criteria, such as attributes of the system which may lead to increased vulnerability to adverse impacts, potential impact categories and thresholds that may indicate low versus elevated vulnerability [4.27].

However, some of these approaches were criticized for the lack of understanding of chemical and physical processes and for simplifying geological models of the CO_2-groundwater-rock systems [4.13]. Thus, naturally occurring CO_2 systems can be used in order to gain additional useful information [4.27], [4.28], [4.29], [4.30], [4.31], [4.32].

4.3. COUNTRY CASE STUDIES

This chapter has been prepared on the basis of the information from the countries participating in the CRP that contributed to the topic of safety/risk assessments, i.e. the Czech Republic, India and Switzerland. Each of these countries had previous experience with radioactive waste disposal, though they are at different levels of programme development. Although the disposal of intermediate level waste (ILW) and low level waste (LLW) is also important, this CRP focused only on high level radioactive waste.

CO_2 disposal is still considered a 'new' technology in the countries involved in this study. Unfortunately, none of the countries with an advanced CO_2 capture and disposal (CCD) status participated in this component of the CRP. Therefore, this chapter compares the state of the art in safety/risk assessment for a segment of the field based on the experience of the countries that share a similar vision that both technologies can exploit the knowledge and know-how of the other.

4.3.1. Czech Republic

The disposal of radioactive waste in geological formations has been studied in the Czech Republic for almost 20 years. Research and assessment of the safe and contained disposal of radioactive waste is the responsibility of the Radioactive Waste Repository Authority (RAWRA). The comprehensive approach, including desk, laboratory and field research and laboratory and natural analogue studies, resulted in the preparation of a preliminary safety case in 2010 [4.33].

On the other hand, the CO_2 disposal programme in the Czech Republic only made the very first steps in the beginning of the 21st century. The potential disposal options were identified, along with the evaluation of potential rock formation disposal capacities [4.34]. Since 2000, only a few projects, focused on general laboratory and field studies for disposal environment characterization, have been launched. Neither a pilot project nor any other CO_2 capture facility has been planned for the near future.

4.3.1.1. Basic concepts

Radioactive waste disposal

All radioactive waste that cannot be stored in near surface disposal facilities (NSDF) in the Czech Republic has to be considered for deep geological disposal. The disposal of radioactive waste relies on the so called multibarrier system that consists of the waste (SF), corrosion resistant canisters and an efficient sealing system. The canisters are embedded in an appropriate host rock formation at a depth of at least 400 m. In the Czech Republic, six potential sites were pre-selected in 2002, all in a crystalline host rock formation.

The safety of the repository would rely on the combined performance of engineered and natural barriers for long term periods of up to one million years. Based on the knowledge of the site where the repository is planned to be built, safety analyses shall clearly and plausibly assess the potential risks, including the period when the repository is closed. The operational safety of a deep repository must meet the same standards as those required of the nuclear and mining industry of the Czech Republic. Post-operational safety is based on the multibarrier principle that should ensure the long term isolation of the waste.

CO_2 geological disposal

In the Czech Republic, CO_2 disposal is likely to be in deep sedimentary aquifers. Some disposal in potential enhanced oil recovery (EOR) fields and injection into coal mines can also be expected [4.34]; however, no site has been selected. Risk assessments will have to be undertaken for both the operational phase and the post-closure phase (considered to be about 1000 years). The monitoring is presumed to be included after closure, as stated in the 2009 EU Directive on geological CO_2 disposal [4.5]. Repository safety would rely on well casing integrity, borehole lining and the surrounding rock. Monitoring would be an inseparable component of the disposal facility life cycle.

4.3.1.2. Definitions and limits

Radioactive waste disposal

The radioactive waste management legislation in the Czech Republic follows the recommendations of IAEA Safety Standards [4.15], according to which one of the main objectives of deep geological disposal is to “isolate spent fuel and high level radioactive wastes from the human environment”. Furthermore, according to Czech legislation, the releases from a repository due to ‘gradual’ processes or disruptive events shall be less than the dose or risk specified. The terms ‘radioactive substance’ and ‘radioactive waste’ are firmly embedded in Czech legislation.

The dose constraint for the safe disposal of radioactive waste, defined in Regulation No. 307/2002 Coll., shall be an effective dose of 0.25 mSv per calendar year for an individual from the critical group of the population. For comparison, the general limit defined in this Regulation is the following: 1 mSv per calendar year for the sum of effective doses from the external exposure and the committed effective doses from internal exposure or exceptionally 5 mSv for a period of five consecutive calendar years.

CO_2 disposal

In the Czech Republic, CO_2 disposal is based on Directive 2009/31/EC of the European Parliament and of the Council on the geological disposal of carbon dioxide [4.5]. The implementation of this Directive into the Czech Republic legislation was accomplished in 2012 with the new Act on CO_2 disposal. The change of other laws was accepted (Act No. 85/2012 Coll.).

CO_2 is not defined in Czech legislation as a dangerous species or as industrial product. In the 'chemical law' REACH, Act No. 356/2003 Coll. in 371/2008c Coll. Version it is stated, that if somebody intends to produce or to import a chemical species, that species must be registered. If it is not registered, it cannot be produced or used in the EU (this became effective on 1 January 2009). According to the authors' opinions, this will be the case for CO_2 produced as part of any technology involved in the production/disposal of CO_2.

The collective release of CO_2 is monitored for the entire Czech Republic (climate protection, Act. No. 695/04 Coll. 12/09 Coll., Act. 351/02 Col. in 417/Coll. Version). However, the limits for CO_2 effects are only partially defined. In the case of the direct CO_2 influence (gas concentration), limits for CO_2 exposure levels for humans in the air are limited by occupation health limits. According to Act No. 178/2001 Coll., the permissible exposition limits are 9000 mg/m^3 and the highest acceptable concentration in the air is 45 000 mg/m^3 (approximately 2.5%). Considering air releases, limits are defined only for carbon monoxide. Moreover, the Act states that the composition and amount of gases released from any waste disposal site or cleaning facility (waste dump) should also be checked. However, parameters and limits are defined individually by the authorized environmental protection authorities, and CO_2 is not usually included in these definitions. No other limits for the quantification of effects of CO_2 on living organisms have been defined in the Act.

The limits for CO_2 content in surface and underground water have not been defined directly in any Czech legislative act. Therefore, they have not been monitored and have not been treated for CO_2 as a parameter influencing human health, the water ecosystem or water sources chemistry. These measures exist only for drinking water, and the CO_2 content only has to be considered for drinking water treatment if the CO_2 content is high. The water is treated by decarbonization. CO_2 may influence the release of substances (tracer metals, etc.) that can directly influence human health and the environment where they can get in drinking water or bath water. This is subject to control in Regulation No. 252/04 Coll.; here, tracer metal content limits for drinking water and hot waters have been defined, including control frequency. The limit values for trace metals in drinking water are on the level of μg/l or the first tens of μg/l.

4.3.1.3. Safety/Risk assessment methodologies

Radioactive waste disposal

A conceptual safety assessment was developed in 2010 [4.33] for a hypothetical site based on analyses of several granite sites in the Czech Massif, including both a geological and a hydrogeological model. The safety assessment started with function analyses of a proposed disposal system. The safety functions were defined as a role through which a repository component contributes to safety, e.g. [4.8], [4.9], [4.10]. The main safety objective of the disposal system was based on legislation requirements (Regulation No. 307/2002 Coll.) *"to provide protection for humans and environment in that way, that effective dose of 0.25 mSv per years for a member of critical inhabitant group was not exceeded with concern to all risks* *in operational and post-closure period."* There, the primary safety function for the proposed disposal system was then formulated as follows: "*to isolate all the radionuclide wastes in the Czech Republic, which cannot be accepted in near surface repositories, in disposal packages and slow down radionuclide migration into the environment after their failure in the way that the limit of 0.25 mSv /year for a person from a critical group of population is not exceeded"* [4.33]. In addition, the following top support safety function was formulated, "*to provide stability for the disposal system against all features, events and processes that can threaten the primary function of the disposal system*". The further derived functions for all system components are site and concept specific.

The next step used in the safety case was scenario development. First, the comprehensive FEP list was collected on the basis of [4.12]. Scenarios developed on the bases of relevant FEP analyses were then defined as follows: the *normal scenario* that includes all the FEPs with a high probability of occurrence in the repository; the *alternative scenario* that can be initiated by FEPs with a low probability of occurrence, which can cause sudden barrier failure and radionuclide release into the environment; and the *intrusive scenario***,** in case of unintentional human breakage into the system and direct human contamination or contamination of inhabitants from contaminated materials.

All of those scenarios, some of which were divided into sub-scenarios, were analysed, and some of them were quantified. The potential release of radionuclides through specified pathways under specific conditions was quantified using mathematical tools, namely the GOLDSIM programme [4.35]. The results of all calculations were then compared with defined limits (0.25mSv/y) and evaluated.

CO_2 disposal

Only basic steps were performed for the safety/risk assessment methodology in the field of CO_2 disposal, but the knowledge of safety assessment methodology for radioactive waste, developed in the last decade at ÚJV Řež, a.s. (formerly the Nuclear Research Institute Řež), will enable the transfer of experience to CO_2 disposal assessments. The very first attempt was undertaken within the Czech research project FR–Tl1/379. To date, the following basic steps have been accomplished: (1) potential CO_2 disposal options have been evaluated [4.34] and information about the systems has been collected, and (2) on the basis of rock system property information, a list of FEPs has been compiled and evaluated [4.34], [4.35], [4.36], [4.37], [4.38], [4.39]. Furthermore, scenarios were developed for both normal and alternative system evolution. The normal scenario involved the evolution of the rock-injection borehole system, keeping the main purpose of CO_2 injection, i.e. to retain CO_2 for the time sufficient to contribute to the decrease of GHG atmosphere content. Moreover, alternative scenarios, including the following cases of non-standard system development, were developed [4.36]:

- CO_2 escape along injection borehole due to rapid pressure increase;
- CO_2 escape along injection and monitoring boreholes – technical accident;
- CO_2 escape along old abandoned boreholes;
- formation and activation of structural faults;
- CO_2 escape along faults;

- CO_2 penetration into the overburden rock;
- CO_2 penetration into the overburden and potential influence on drinking water supply.

Some of the mathematical codes that can be used for the quantification of radionuclide release (e.g. PHREEQC, TOUGH2/TOUGHREACT, GOLDSIM [4.35], [4.36], [4.38]) were tested for both laboratory and real scale tasks. However, neither the safety case nor any other advance safety assessment approach was adopted. Moreover, there are no direct limits for CO_2 effects defined in the legislation, except occupational limits, that would be able to be used for comparison with results of exposure calculations.

4.3.2. Switzerland

Research and assessment of the safe and contained disposal of radioactive waste is the responsibility of the National Cooperative for the Disposal of Radioactive Waste (NAGRA), which was founded in 1972 and represents the Swiss nuclear energy industry and others using radioactive material (industry, research and medicine). The findings and proposals of the NAGRA are then assessed by the Swiss Federal Nuclear Safety Inspectorate (ENSI), which is the national regulatory authority with the responsibility for nuclear energy, including radioactive waste disposal.

A comprehensive approach, including desk, laboratory and field research and natural analogue studies, has led to the identification of six potential sites and the identification of the relevant safety issues [4.40].

The options for CO_2 disposal are being assessed within the ongoing Carbon Management in Power Generation (CARMA) research project. With only a very small fraction of electricity produced in Switzerland coming from fossil fuel power plants (<5%), the objectives of CARMA focus largely on future energy options and knowledge export. The largest point source emitters of CO_2 in Switzerland are industrial facilities, particularly cement production. The current annual emission of CO_2 from industrial sources in Switzerland is approximately 11.3 Mt [4.41].

4.3.2.1. Basic concepts

Radioactive waste disposal

The concept of the deep geological radioactive waste repository is based on the so called multibarrier system that consists of a stable waste form, corrosion resistant canisters and an efficient sealing system being embedded into an appropriate host rock. The safety of the repository relies on the combined performance of both engineered and natural barriers for long term periods of up to about one million years. The NAGRA identified six potential locations for the siting of radioactive waste repositories, three of which are suitable only for LLW and short lived ILW, and three of which are suitable for SF, HLW and long lived ILW, and also, therefore, for LLW.

The proposed final disposal facility for radioactive waste is a series of horizontal emplacement tunnels located at a depth of approximately 650 m in the centre of the Opalinus Clay formation. The Opalinus Clay has a self sealing capacity that reduces the effects of fractures.

CO_2 disposal

A first appraisal of the potential for deep geological disposal of CO_2 in Switzerland was made by Chevalier and Diamond [4.42]. Following a numerical scoring and weighting scheme on a scale of 0–1, they determined that the combined volumes of the four main candidate aquifers with potentials above 0.6 offer a theoretical, effective disposal capacity of 2680 Mt CO_2. Future fossil fuelled power stations in Switzerland would most probably be natural gas combined cycle plants, due to the lack of inland fossil resources, the existence of natural gas pipelines and the lower CO_2 emissions per kW·h of natural gas compared with coal. A 400 MW combined cycle gas power station produces approximately 0.7 million t CO_2/year (assuming 360 kg/MW·h and 5000 hours/year operation), and the research, therefore, concluded that more than a sufficient capacity for CCD from electricity generation and other industrial activities exists to serve the needs of many decades. This is, however, only a preliminary study based on the literature, and the actual disposal potential may prove to be very different following more physical geological examinations of the area.

4.3.2.2. Definitions and limits

Radioactive waste disposal

The basic regulations for radionuclide disposal in Switzerland are the Swiss Nuclear Law (KEG) and the Swiss Regulatory Guideline HSK-R-21. The overall objectives of radioactive waste disposal and the principles to be observed, which are stated in the HSK-R-21 guideline, are derived from the requirements. As a specification of the overall objective and the associated principles, the safety requirements are expressed in the form of three protection objectives [4.43]:

- The release of radionuclides from a sealed repository, subsequent upon processes and events reasonably expectable to happen, shall, at no time, give rise to individual doses which exceed 0.1 mSv per year;

- The individual radiological risk of fatality from a sealed repository, subsequent upon unlikely processes and events not taken into consideration in (1), shall, at no time, exceed one in a million per year;

- After a repository has been sealed, no further measures shall be necessary to ensure safety. The repository must be designed in such a way that it can be sealed within a few years;

- For the identification of suitable potential locations for a geological repository, the ENSI [4.43] has defined three safety criteria categories, as shown in Table 4.1.

A more comprehensive explanation of each of the criteria can be found in the ENSI report [4.43].

The dose constraint for safe disposal of radioactive waste shall be an effective dose of 0.1 mSv per calendar year for an individual from the critical group of the population.

TABLE 4.1. SAFETY CATEGORIES AND CRITERIA FOR THE ASSESSMENT OF PROPOSED DEEP GEOLOGICAL REPOSITORIES FOR RADIOACTIVE WASTE IN SWITZERLAND [4.42]

Safety categories	Safety criteria
Properties of the host rock	Spatial dispersion
	Effectiveness of hydraulic barriers
	Geochemical conditions
	Release pathways
Long term stability	Stability of the location and rock layer properties
	Influence of erosion
	Disposal specific influences
	Use conflicts
Reliability of the geological conclusions	Ability to characterize the rock layers
	Ability to examine the special conditions
	Ability to predict the long term changes

CO_2

The definitions and limits of CO_2 in Switzerland have not yet been defined.

4.3.2.3. Safety/Risk assessment methodologies

Radioactive waste disposal

The Swiss safety assessment approach was demonstrated, e.g. in a safety report on the demonstration of disposal feasibility for SF, vitrified HLW and long lived ILW [4.43]. The safety case was constructed for the case of the long term safety of a repository for SF, HLW and ILW located in the Opalinus Clay.

The safety case, in this reasoning, is the set of arguments and analyses used to justify the conclusion that a specific repository system will be safe. It also includes a presentation of evidence that all relevant regulatory safety criteria can be met. Moreover, it includes a series of documents that describe the system design and safety functions, illustrate the performance and present the evidence that supports the arguments and analyses. Also discussed is the significance of any uncertainties or open questions in the context of decision making for further repository development.

The preparation of the safety case involved several steps [4.44]:

- Definition of disposal system;
- System concept development;
- Safety concept derivation;
- Scenario development, concerning different radiological consequences;
- The safety case that is compiled from the arguments and analyses.

Safety assessments of the proposed radioactive waste disposal will be carried out by the ENSI in the second stage of the radioactive waste disposal plan. The ENSI will evaluate the proposed sites (a minimum of 2) based on the safety criteria described in Table 4.1.

CO_2 disposal

Safety/risk assessment methodologies have not yet been applied to potential CO_2 disposal sites in Switzerland. The risks related to CCD, in terms of accidents with human health consequences, were analysed and reviewed by [4.45]. Due to the lack of long term experience and comprehensive baseline data, the frequency of occurrence of hazardous events and accidents with CO_2, in relation to the injection and disposal of CO_2, had to be approximated by:

- Industrial experience with CO_2 injection and disposal in CCD components (CO_2 disposal projects, data on accidents with CO_2 at offshore platforms, CO_2 EOR well failures, CO_2 EOR well blowouts);

- Industrial experience with analogue technologies (e.g. leakage experience from natural gas storage, acid gas injection well failures, etc.). Additionally, the estimates from offshore activities are considered;

- Experience with natural events (volcanic eruptions, natural CO_2 fields, etc.).

The Swiss conceptual model consists of a generic capture unit, transport by pipeline, injection plant and two injection wells. Injection well failures and leakage during disposal were also considered, and from these, a cumulative ‘event rate’ for one such concept operating for one year was determined (see Table 4.2). Two scenarios were analysed:

- 200 km pipeline without recompression, 2 injection wells;

- 400 km pipeline including 1 recompression, 2 injection wells.

TABLE 4.2. FREQUENCY OF HAZARDOUS SITUATIONS FOR THE CCD PROCESS IN A GENERIC SWISS CCD MODEL SOURCE: [4.45].

Module	Scenario 1	Scenario 2
CO_2 capture	$1 \times 1.6 \times 10^{-1}$	$1 \times 1.6 \times 10^{-1}$
Pipeline convergence (100 m)	$1 \times 4.6 \times 10^{-1}$	$1 \times 4.6 \times 10^{-1}$
Pipelines	$40 \times 2.5 \times 10^{-1}$	$40 \times 7.4 \times 10^{-1}$
Injection plant	$1 \times 1.8 \times 10^{-1}$	$1 \times 1.8 \times 10^{-1}$
Injection pipe (× 2)	$2 \times 2.1 \times 10^{-4}$	$2 \times 2.1 \times 10^{-4}$
Post-closure injection pipe failure	$2 \times 4.0 \times 10^{-2}$	$2 \times 4.0 \times 10^{-2}$
Geological disposal	$1 \times 1.9 \times 10^{-4}$	$1 \times 1.9 \times 10^{-4}$
Failure rate per year of CCD	0.52	0.72

The results of the analysis showed that a hazardous situation could occur as frequently as every 1.4 years. The injection plant can have one of the highest frequency rates among the above ground operations, equating to one hazardous situation every 5.6 years.

4.3.3. India

In India, all types of radioactive waste are managed in a manner that ensures compliance with the fundamental principles of radiation protection and environmental safety [4.46]. The country has extensive experience, spanning over more than four decades of disposal of LLW and ILW in NSDFs (seven operating). The studies on deep geological disposal of HLW have also been carried out at a moderate pace over the last four decades.

The study of geological disposal of CO_2 in India has been performed at a modest pace, with few institutes and universities conducting isolated and independent studies. Most of the reported studies focus on the estimation of CO_2 disposal potential in various geological formations in India. A few experimental studies, dealing mainly with mineral carbonation in basaltic rocks, are also available. Recently, Bajpai et al. have completed a comparative study on disposal facilities for radioactive waste and CO_2 [4.47].

4.3.3.1. Basic concepts

Radioactive waste disposal

In India, the Atomic Energy Regulatory Board (AERB) acts as an independent regulator and is responsible for defining the specific basic requirements for the safe management of radioactive waste from nuclear and radiation facilities. Waste management and disposal is carried out in line with the principles defined by [4.46].

The general philosophy for radioactive waste management being followed in India is as follows:

- Retention and gradual decay of short lived radionuclides;
- Concentrate and contain activity as practicable;
- Dilute and disperse LLW within the authorized limits.

The reference disposal system adopted in India relies on a multibarrier system, i.e. waste form being inserted into stainless steel canisters, clay buffer and surrounding overpack. The thickness of clay buffers has been optimized, based on heat flux dissipation capacity and the ability to retain fission products over the entire span of the thermal phase of the geological repository, i.e. 500 years [4.48]; that is to say, the system fulfils its safety function. The site selection campaign, involving detailed geological, hydrogeological, rock mechanical and socioeconomic studies, has rendered about 22 promising zones with good homogeneous granites in different part of the country in 2000 [4.49].

CO_2 disposal

Currently, there is no pilot or commercial scale CCD project going on in India; therefore, technical, social and economic data are unavailable. Additionally, few researchers have compiled geological and geographical data on the geological disposal of CO_2 in India. Initial studies indicate that there are potential disposal sites on the subcontinent and along the immediate offshore regions on the Arabian Sea (south-west coast) and Bay of Bengal (south-east coast, [4.50]. In 2006, Singh et al. made initial attempts to evaluate the disposal potential in India and estimated that roughly 5 Gt CO_2 could be stored in unmineable coal seams, 7 Gt CO_2 in depleted oil and gas reservoirs, 360 Gt CO_2 in offshore and onshore deep saline aquifers and 200 Gt CO_2 via mineralization in basalt rocks [4.51]. A recent study conducted for the International Energy Agency Greenhouse Gas R&D Programme has revised the estimates first made by [4.51]. Their study concludes that more realistic disposal capacities for saline aquifers need to be quantified, most likely with the aid of oil and gas exploration information, such as seismic and well data.

4.3.3.2. Definitions and limits

Radioactive waste disposal

In India, radioactive waste is defined as, "*Material, whatever its physical form, left over from practices or interventions for which no further use is foreseen: (a) that contains or is contaminated with radioactive substances and has an activity or activity concentration higher than the level for clearance from regulatory requirements, and (b) exposure to which is not excluded from regulatory control*" [4.52]. There are extensive guidelines, in the form of safety codes, standards and guides, issued by the AERB concerning NSDFs for LLW and ILW. However, the preparation of similar regulatory standards and guides in respect of deep geological repositories is in progress.

The effective dose limit defined by the sum of effective doses from external as well as internal sources, as set by the AERB [4.53], for occupational workers is 20 mSv/year averaged over five consecutive years, with an effective dose of 30 mSv/year in any single year. The limit of effective dose to members of the public has been set as 1 mSv/year. The radiation dose to the critical group or the general public from all exposure pathways should not exceed the limits prescribed by the AERB (0.5 mSv/year). However, dose limits for deep geological repositories have yet to be defined.

CO_2 disposal

CO_2 is not classified as dangerous in the Indian air quality standard; rather, limits are defined only for carbon monoxide in industrial and public areas by the Indian Standard (IS). Such limits are not in direct relation with CO_2 disposal.

4.3.3.3. Safety/risk assessment methodologies

Radioactive waste disposal

Extensive expertise in a safety assessment for evaluating the performance of a disposal facility, as a whole and its components individually, to predict the potential radiological impact on the public and environment has been developed in India over the last four decades to demonstrate safety offered by operating waste disposal facilities, i.e. NSDFs. The safety assessment methodology considers the disposal facility and its environment as a system. This takes into account the waste inventory, the features of engineered and geological barriers, the time frame, the uncertainty in the parameters and modelling. The main components of such assessments are as follows:

- Compilation of a FEP list;
- Generation of scenarios, their screening and analysis;
- Potential pathways identification (excavation damage zone, fractures, etc.);
- Site geological and hydrogeological data acquisition;
- Model and software development, validation and verification;
- Presentation of the analyses results.

Important data used for safety assessments include waste and container characteristics, disposal facility details, site characteristics, biosphere characteristics, demographic and socioeconomic characteristics and monitoring data.

In the case of all seven operating NSDFs, while complete safety cases have not been generated, the identification of FEPs, scenario generation, site geological and hydrogeological data acquisition and pathway detection have been carried out, as in the case of a potential deep geological repository. The doses to members of the public from NSDFs, through groundwater pathways as well as marine exposure pathways, have been estimated well below the regular limits. The typical dose to members of the public located at 800 m distance from the waste disposal facility NSDF through drinking water in the case of a coastal facility is shown in Table 4.3 [4 54]. The general three dimensional, time dependent advection diffusion equation of a radionuclide through a porous medium has been used for these calculations. The methodology is applicable in the same way for deep geological repository.

The dose limit and dose estimations for radioactive waste deep geological repository are under development. The assessment of the possible dose to members of the public from a deep geological repository through groundwater pathways under various scenarios has yet to be taken up. Nevertheless, a similar approach is expected to be used in this case, as well.

TABLE 4.3. ESTIMATED DOSES TO MEMBERS OF THE PUBLIC FROM THE WASTE DISPOSAL FACILITY (SV/YEAR)

N	Pathways					
	Ground-water drinking pathway	Marine exposure pathway (Sv/year)			Human intrusion pathway (Sv/year)	
	Ingestion	Ingestion	Inhalation	External	Dwelling inhalation	Excavation inhalation
^{137}Cs	-	2.60×10^{-20}	2.66×10^{-26}	7.50×10^{-20}	1.26×10^{-10}	1.88×10^{-10}
^{90}Sr	1.82×10^{-28}	2.55×10^{-7}	4.17×10^{-12}	8.25×10^{-12}	4.82×10^{-11}	7.27×10^{-11}

CO_2 disposal

No specific safety assessment cases have been reported with respect to CO_2 disposal in India. However, safety assessment methodology and mathematical models developed for dual phase (liquid and gas) transport modelling, currently used for the radioactive waste disposal facility, could be applicable to CO_2 injections. It can also be envisaged that the development of the safety case would involve scenario development, identification of FEPs operating over the disposal site, etc. The potential use of relevant natural analogues, as utilized in assisting the understanding for the disposal of radioactive waste, will also assist understanding the processes involved in the geological disposal of CO_2.

4.4. COMPARATIVE ASSESSMENT

The results of this case study sum up and compare the national experiences of the Czech Republic, Switzerland and India in the field of safety/risk assessment of radioactive waste and CO_2 disposal. The practical information is confronted with a general basis for both fields, finding useful information that can be used later in other comparative studies for other countries. All the countries involved had previous experience in radioactive waste disposal, though they are at different levels of programme maturity. Although ILW and LLW disposal are important, the focus here was specifically on long lasting radioactive waste.

On the other hand, CO_2 disposal technology is still considered a 'new' technology for all the countries involved in this study. Unfortunately, none of the countries with advanced CO_2 disposal status took the part in this part of the CRP; therefore, this chapter compares the state of the art in safety/risk assessment for a segment of the field based on the experience of countries that share the similar vision that both technologies can exploit the knowledge and know-how of each other.

Both technologies are used to dispose of the products of anthropogenic energy production into the geosphere. Moreover, their goals are the same: to find a safe, effective approach to keeping the waste material deep underground until its properties would not endanger humans or the environment. Nuclear power stations have been in operation for more than 40 years. The disposal of radioactive waste seems to be an inevitable problem to be solved in the near future, so as not to shift the nuclear burden to the next generations. Fossil fuel energy production has been facing the problem of climate change, due to the greenhouse effect to which specific gases contribute. Even though CO_2 disposal technology is still under development, a fast and rapid progress might enable its early employment. Having similar goals, both technologies might, therefore, exchange experiences and progressive approaches from one to the other. On the other hand, there are also many differences between the geological disposal of radioactive waste and CO_2.

Any geological disposal facility has to meet relevant safety standards that are specified and approved in order to get licenced. Barrier system behaviour and performance during defined timescales have to be assessed and evaluated against defined limits. During the operational period and shortly after the closure of the repository, mitigation actions can be undertaken in case of unfavourable disposal system performance. However, long term safe performance in the post-closure period has to be carefully predicted for any case in order to fulfil the regulator and licence provider requirements concerning repository safety.

In the Czech Republic, India and Switzerland, radioactive waste disposal is managed by the responsible state authorities. Each of these countries has more extensive experience with radioactive waste management than with CO_2 disposal management, though the maturity of the radioactive waste programmes differs between countries. Nuclear power stations have been in operation in these countries for decades and they are planned to be built in the Czech Republic and India, but not in Switzerland. In these countries, the disposal concept is based on the multibarrier concept, i.e. container, engineered barrier and host rock, which has safety functions that ensure the safe performance of the facility over a long period of time. Different host rock concepts already exist in the world, varying between clay rock (Switzerland) and crystalline rock (Czech Republic, India) for the involved countries (see Table 4.4).

TABLE 4.4. DISPOSAL CONCEPTS AND SITE SELECTION

	Czech Republic	Switzerland	India
Radioactive waste	Geological Direct SF disposal into crystalline rock 500 m depth Multibarrier concept Granite 6 potential sites pre-selected	Geological Processed HLW and direct disposal of conditioned SF 650 m Multibarrier concept Clay rock 6 potential sites for LLW and ILW 4 different formations 3 potential sites for radioactive waste, all Opalinus clay formations	Geological Processed HLW 600–700 m Multibarrier concept Granite 22 promising regions selected; one potential site studied in detail
CO_2	Onshore CO_2 disposal only Saline aquifers Hydrocarbon fields and coal measures: minor No selection of overall geology or site undertaken to date	Onshore CO_2 disposal only Ongoing feasibility assessment of geological disposal of CO_2 in Switzerland	Both onshore and offshore disposal possible Inland alluvium planes of major river systems Unmineable coal measures Offshore saline aquifers No pilot studies to date

The countries taking part in this comparative study have implemented the definition of radioactive substances and wastes into their national legislations. Without any exception, these countries have included the definition of the reference value (limits) in their legislation. The reference value is the key parameter to which a safety indicator should be compared in order to evaluate repository safety and performance [4.2]. All these countries used the effective dose constraints as a reference value in their reference documents (see Table 4.5). According to this approach, the effective dose provides a practicable approach to the limitation of radiation risk in relation to both occupational exposures and exposures of members of critical inhabitant groups [4.8]. The values are 0.1 and 0.25 mSv/y for members of the critical group for Switzerland and Czech Republic, respectively, i.e. they are at similar levels as those identified in [4.8]. However, precise safety limits values have not yet been defined for safe radioactive waste disposal in India. Therefore, the value of 0.5 mSv can be considered as a preliminary one.

The most recommended procedure for both radioactive waste and CO_2 disposal facilities includes the following steps [4.10]: concept and system description, scenario development and evaluation, model development and employment, consequence analyses and evaluation towards safety constraint. The time period is usually defined for the safe performance of radioactive waste disposal (one million years in the Czech Republic and Switzerland), but it is not strictly defined for CO_2 geological disposal (usually assumed to be one thousand years).

The previously mentioned safety assessment methodologies for radioactive waste disposal were available in the Czech Republic, India and Switzerland. Those approaches were based on the safety functions of all barriers present in the disposal system. All three countries involved in this study have undertaken at least a preliminary safety assessment study for LLW, ILW or radioactive waste. The most advanced stage was reached in Switzerland, where disposal feasibility was demonstrated for both ILW and HLW [4.44].

Studies on CO_2 geological disposal have recently advanced at a decent pace in the countries of this study. However, none of these countries plan to open a CCD facility in the near future. Essentially, the EU countries (the Czech Republic) should base CO_2 geological disposal on Directive 2009/31/EC of the European Parliament and of the Council on the geological disposal of carbon dioxide [4.5]. According to this document, the disposal could be performed by individual operators that would obtain a license from the regulatory body after declaring the safe performance of the disposal system. Therefore, no central disposal agency is supposed to exist. The requirements for safety assessments are included in the 2009 Directive [4.5] and in the respective guidance documents [4.55], though they are defined rather loosely.

The safety of CO_2 disposal is generally supposed to rely on well integrity and the rock formation safety function (see Table 4.4). No specific requirements regarding CO_2 stream composition were found for condensed or supersaturated injection, either in national legislations or in international requirements or recommendations. The supersaturated state is presumed for injection below 800 m from the surface. According to the countries' respective available rock environments, CO_2 disposal would be performed either onshore (the Czech Republic, Switzerland, India) and/or under the sea bed (offshore; India) – see Table 4.4. The appropriate rock formations varied between deep saline aquifers, hydrocarbon fields, unmined coal seams and basalts. However, neither a final formation nor a final site has been selected in any of the countries in question.

TABLE 4.5. EXPOSURE DEFINITION AND PERIODS OF SAFETY/RISK ASSESSMENT

	Czech Republic		Switzerland		India	
	Exposure definition: Limits for safety/risk evaluation	Periods of safety/risk assessment	Exposure definition: Limits for safety/risk evaluation	Periods of safety/risk assessment	Exposure definition: Limits for safety/risk evaluation	Periods of safety/risk assessment
Radioactive waste	Dose (0.25 mSv/year)	Operational: safety during construction and disposal Post-closure: 10^6 years	Dose (0.1 mSv/year)	Post-closure: The required functional lifetime of a HLW container is 10^4 years Multibarrier system: 10^6 years	Dose (0.5 mSv/y) for NSDF For geological disposal, limits yet to be defined	Operational: safety during construction and disposal Post-closure: yet to be defined
CO_2	CO_2 concentration in the air (occupation exposure) CO_2 concentration in the water (not fully defined) Major species, trace metal and hazardous compound concentration in water (potable water requirements)	Operational: during injection and closure Likely to be 10^3 years	CO_2 concentration in the air CO_2 concentration in the water Major and trace metals concentration in water	Operational: during injection and closure Likely to be 10^3 years	CO_2 concentration in the air CO_2 concentration in the water Major and trace metals concentration in water	Operational: during injection and closure Post-closure: Yet to be defined

There is a clear lack of strict limited safety constraint levels for the impact of CO_2 on surrounding humans and biota. Moreover, there is no definition of CO_2 as a material to be disposed of. This part seems to be most problematic in the assessment of both local and global impacts for possible irregularities after CO_2 injection in all the countries. Partially, such a CO_2 leakage might be limited by occupational exposure values defined by legislations, namely for the short term assessment period (the operational period and the monitoring period). However, the limits for long term CO_2 influence, namely the gas and dissolved gas content in water, are not strictly defined, as the substance is not considered as a hazardous one. The effect associated with potential trace metal release or brine displacement can be loosely compared to the limits for acceptable trace metals in the composition in drinking water. However, such regulatory steps towards the legislative definitions of appropriate limits have not been made either at the national or at the international level. The comparison of the Czech Republic, Switzerland and India is given in Table 4.5.

For CO_2 disposal, the involved countries assume that a similar safety/risk assessment methodology to that used for the radioactive waste safety/risk assessment approach will be used. However, a specific safety/risk management programme has not been established in any of these countries. The methodology would, presumably, consider borehole integrity and host rock safety functions. Furthermore, only a few laboratory experiments have been performed in the participating countries, so far, that have aimed to study the migration and interaction of CO_2 in potential host rock environments. A summary is given in Table 4.6.

4.5. CONCLUSIONS

The results of this study are the outcome of a cross national intercomparison of safety/risk assessment methodologies of disposal facilities for radioactive waste and CO_2 in the Czech Republic, India and Switzerland. The main aims were as follows:

- To identify the state of the art of the safety/risk assessment for both disposal options in the countries involved;
- To identify the status of the safety/risk assessment for both disposal options in the countries involved;
- To identify what lessons can be learnt from their intercomparison, though they are at different levels of programme maturity.

A safety/risk assessment can be defined as a systematic analysis of the hazards associated with a geological disposal facility, and the ability of the site and design to provide the safety functions and meet technical requirements so that the facility performs safely for defined time periods. Clearly, the disposal facility for any type of waste or hazardous substance should prove to be safe in order to receive the licence. In order to fulfil such requirements, the safety requirements have to be clearly defined in order to be comparable with results of the disposal system evolution assessment over defined timescales. Hereby, we can find one of the major differences between radioactive waste and CO_2 disposal: strictly defined safety constraints are lacking for CO_2 disposal.

TABLE 4.6. SAFETY/ RISK ASSESSMENT METHODOLOGIES

	Czech Republic	Switzerland	India
Radioactive waste	Based on evaluation of safe performance of multibarrier system components. Based on Swedish SKB approach: System description, safety function analyses for system components, FEP list collection, scenario development, modelling. Safety case (arguments, evidence, analyses).	Base on safety function analyses for all system components, Modelling, safety case (arguments, evidence, analyses).	Based on evaluation of safe performance of system components. Well established safety assessment methodology for NSDF exists. Same to be extended to geological repository involving fracture flows over very large time periods
CO_2	Most probably to follow radioactive waste approach, however not fully specified	Not fully specified	Not fully specified

The safety, safety requirements and recommendations, including safety indicators and safety assessment procedures for radioactive waste disposal, have been broadly defined in above mentioned IAEA and NEA/OECD documents. These form the global basis that has been implemented into the national legislations. An additional approach that should unite radioactive waste management framework in EU Member States, such as the Czech Republic, is the 2011 EU Directive on the responsible and safe management of spent fuel and radioactive waste [4.56].

Such an approach differs from CO_2 disposal. While nowadays there exist a rather broad range of scientific results and documents for CO_2 safety/risk assessment methodologies, one cannot find so many unifying official documents that would clearly define basic steps and constraints for such procedures. One of such rare documents is the 2009 EU Directive on CO_2 disposal [4.5]. However, the requirements on the risk analyses procedures are rather generally defined here, even though the risk analyses is stated to be an inevitable part of the licence application [4.5].

Moreover, the definition of reference levels (constraints) is less straightforward for CO_2 disposal risk assessments, as CO_2 hazard levels are not usually directly defined in national legislations. CO_2 levels in the air usually refer to occupational exposures. Even indirect CO_2 effects (groundwater quality, tracer metal content) usually have to refer to occupational levels or to groundwater quality measures. A more global unifying process would help during the process of safety/risk assessment and decision of procedures and tools. We also have to take into account that the injection of enormous volumes of CO_2 into deep located underground rock horizons would not always be only a national case, namely onshore. The threshold definition of the following safety indicators should be considered, according to different timescales to be taken into account during system performance evaluation:

- CO_2 level in the air (operational safety, short term safety);
- CO_2 level in water/pH (short term safety and long term safety: groundwater and potable water quality);
- Concentration of defined species in the groundwater/potable water (short term and long term safety: increased salinity – Na^+, Cl^- trace metals).

Some of the safety/risk assessment methodologies are used for both radioactive waste and CO_2 disposal, following the schemes outlined in international recommendations of the IAEA and NEA. Essentially, the following items would be included in safety/risk assessment for both fields:

- System description;
- Scenario development;
- Model development;
- Consequence analyses.

The system description and scenario development, followed by consequential analyses, are the most common tools for both fields. FEP lists and scenarios for disposal system development also often used. However, most of the CO_2 disposal safety assessments performed have not launched the safety case approach.

On the other hand, other safety assessment approaches have also been used for CO_2 disposal risk evaluation, even using the experience from other CO_2 using technologies (e.g. EOR). The outline of these assessments usually have intuitively fulfilled general scheme, outlined in Guidance Document 1 for implementation of the 2009 EU Directive on CO_2 disposal [4.55]:

- Risk identification and assessment;
- Risk ranking;
- Risk management measures.

As stated above, the cross national comparison included countries that were willing to participate due to their involvement in IAEA CRP project. Therefore, the case study cannot include information from a wide range of countries with different level of programme maturity. These countries are considering the disposal of radioactive waste on their territory. All of these countries have undertaken experience with safety assessment projects in the past, at least for LLW and ILW repositories (India) or even for radioactive waste disposal (Switzerland, the Czech Republic). Following the statements above, each of these countries in the cross national comparison have implemented the global requirements for radioactive waste into the national legislations, where safety constraints, usually the effective dose for a member of the inhabitant critical group, can then be found. The values surely differ, as they are based on national legislations and national safety requirements. Additional safety indicators in radioactive waste safety assessment have been recommended, namely due to the long timescales in which disposal performance system is evaluated.

In all of the countries involved in this study, CO_2 disposal programmes have reached only the very first steps of development. These countries have identified potential regions where the CO_2 disposal would be possible, including, in one case, offshore disposal (India). Only the basis for further safety procedures was laid out.

Having experience with radioactive waste disposal safety assessment, the participants from the Czech Republic, India and Switzerland presumed that the experience from this field should also be used for CO_2 disposal and that safety case development procedures should be followed. However, this can be considered only as an opinion of the authors and need not to be valid in the future. As CO_2 can be injected by an independent operator and central governance is missing here, it would be the responsibility of each individual implementer to declare the safe performance of a CO_2 disposal facility [4.5]. Additionally considering the lack of strictly defined safety/risk procedures, each permit applicant could use any procedure that would lead to the required proof of safe repository performance.

Summing up the results of cross national comparison and taking into account general information about state of the art, it seems that the CO_2 disposal field would benefit from having a definition of such a straightforward concept of safety requirements such as those in the radioactive waste field. Such requirements could be, consequently, implemented into national legislations, enabling easier evaluation of long term repository performance. The limits for CO_2 levels or any other complementary indicator are not directly defined, even in the 2009 CO_2 Directive [4.5], obligatory for EU Member States (the Czech Republic). A unified procedure for both a defined CO_2 limit and safety/risk assessment procedures would be useful, namely in the case of small countries, for example the Czech Republic or Switzerland, as mentioned above.

However, further experience has arisen during the cross country intercomparison. There is another topic that can be transferred from the radioactive waste disposal field to the CO_2 disposal: the communication of safety/risk assessment results with civil society. This topic is discussed in Chapter 7 of this report.

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Chapter 5

MONITORING

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5.1. INTRODUCTION

A reliable and cost effective monitoring programme is an important part of making geological disposal a safe, effective and acceptable method for radioactive waste and carbon dioxide (CO_2) disposal. Monitoring is necessary to demonstrate that the disposal project meets these requirements. Regulatory agencies require the verification that the practice of geological disposal is so safe that it does not have significant, adverse, local environmental impacts. Thus, monitoring is required as a part of the licensing process for geological disposal of radioactive waste and CO_2.

For radioactive waste disposal, monitoring is required to examine the protection and safety of the repository. Monitoring programmes need to cover several important issues, such as the degradation of repository structures, waste packages and buffer materials. The programmes need to monitor chemical and physical interactions between introduced materials, groundwater and host rock near field, as well as the surrounding environments. In addition, the programme needs to monitor the releases of radioactive substances in the environment from the repository.

Monitoring in CO_2 disposal is required to demonstrate that CO_2 is safely and successfully contained within the disposal zone. The requirements for CO_2 monitoring need to cover two critical issues. The programme should monitor the location of the plume of separate phase CO_2, either as supercritical fluid or gas in the subsurface. If there is evidence that significant leakage has occurred from the primary disposal structure and CO_2 has migrated to the land surface, methods for monitoring the concentration and flux of CO_2 at the land surface are highly desirable. Monitoring is also required to ensure effective injection by tracking the condition of the injection well, injection rates, wellhead pressures and formation pressures.

The main objectives of monitoring radioactive waste and CO_2 disposal facilities depend, to a large extent, on the stage of development of the disposal site. These objectives include providing information to ensure that operations are conducted in a safe and environmentally acceptable manner. The monitoring programme aims to enhance public acceptance and assist in the decision making process by providing data. In addition, information from the monitoring programme can be used in safety assessment calculations. CO_2 disposal projects provide an analogy to radioactive waste disposal, which is the removal of material from the surface of earth and the disposal in the subsurface with isolation and containment of the waste surrounded by the host rock. Monitoring the evolution of CO_2 injected into the sub-surface provides an analogue to the monitoring of radionuclides, gas and the introduced materials following the emplacement of radioactive waste in the underground repository.

5.2. MONITORING OF RADIOACTIVE WASTE DISPOSAL FACILITES

International guidance on repository monitoring has been prepared by the International Atomic Energy Agency (IAEA) [5.1], [5.2]. The IAEA defines the monitoring of geological repositories for radioactive waste as follows:

> *"Continuous or periodic observations and measurements of engineering, environmental or radiological parameters, to help evaluate the behaviour of components of the repository system, or the impacts of the repository and its operation on the environment." (*[5.1], p.1)

Most countries that are developing radioactive waste disposal programmes need to adopt this guidance and develop their own monitoring programmes. The IAEA suggests that Member States adopt the standards for the protection of health and minimization of danger to life and property in the following statement:

> *"A programme of monitoring shall be carried out prior to, and during, the construction and operation of a disposal facility and after its closure, if this is part of the safety case. This programme shall be designed to collect and update information necessary for the purposes of protection and safety. ... Monitoring shall also be carried out to confirm the absence of any conditions that could affect the safety of the facility after closure." ([5.2], p. 40)*

An additional role of the monitoring programme is to build confidence in the long term safety case and demonstrate that the facility is evolving as expected. Monitoring is necessary to build confidence in the construction and operation of the facility and to demonstrate its appropriate environmental performance. Thus, information provided by monitoring supports public acceptability and management decisions of radioactive waste disposal.

The requirements of the monitoring programme for a radioactive waste disposal facility include collecting and updating information to confirm the conditions affecting the safety of workers and members of the public and the protection of the environment during the operation of the facility, and to confirm the absence of any condition that could reduce the post-closure safety of the facility.

The IAEA also recognizes that:

> *"The extent and nature of monitoring will change throughout the various stages of repository development, and monitoring plans drawn up at an early stage of a programme will need to reflect this. It may also be expected that the plans will be revised periodically in response to technological developments in monitoring equipment, modifications to the repository design and changing societal demands for information." ([5.1], p. 1)*

The IAEA defines the primary objectives of monitoring geological radioactive waste disposal systems as follows [5.2]:

1) to provide information for making management decisions;

2) to understand a repository system behaviour and develop the safety case for the repository;

3) to test further models to predict these aspect;

4) to provide information to give society the confidence to take decisions on the major stages of the repository development;

5) to strengthen confidence that the repository is having no undesirable impacts on human health and the environment;

6) to accumulate an environmental database on the repository site and its surroundings for future decision makers;

7) to address the requirement to maintain nuclear safeguards.

The IAEA also recognizes operational reasons for monitoring, common to any nuclear facility [5.2]:

8) to determine any radiological impacts of the operational disposal system on the personnel and the general population;

9) to determine non-radiological impacts on the environment surrounding the repository, such as impacts of excavation and surface construction on local water supply and water quality;

10) to satisfy non-nuclear industrial safety requirements for an underground facility, such as dust, gas, noise, etc.

5.2.1. Phases of radioactive waste disposal and related monitoring activities

5.2.1.1. Pre-operational phase

The extent and nature of the monitoring programme change through various stages of repository development. During the planning of the repository, the potential site is studied to determine its ability to confine the radioactive waste and to protect people and the environment. Monitoring plans need to be set up at an early stage of the repository development programme. It is important to collect, as early as possible, good baseline data which are representative of undisturbed conditions during the pre-operational phase.

During pre-operational monitoring, data are collected and evaluated at and around the proposed site. The frequency of data measurements should be high enough to identify characteristics that are subject to temporal variations, if there are any.

Pre-operational monitoring should be performed to establish the baseline of environmental conditions, including geological, hydrogeological and geochemical parameters and radiation levels, to determine the impacts of the source by measuring the same parameters. At this stage, environmental monitoring is designed to measure existing activity concentrations and radiation dose rates in the environment. It is also necessary to investigate local factors that might affect the doses received by individuals in the population, such as meteorological, hydrological and geochemical characteristics in the aquatic environment, population distribution and land use [5.3].

The expected inventories of radionuclides during operation of the facility should also be made in the pre-operational assessments. These assessments should consider the possible discharge pathways and the expected amounts of radionuclides discharged into the environment from the facilities. The monitoring network and the environmental sampling regime should be established on the basis of this information [5.4].

5.2.1.2. Operational phase

Monitoring activities during the operational phase are similar for all nuclear facilities. Such monitoring is designed to demonstrate that there is no significant release of radioactive materials, which could impact humans or the environment. In case of significant releases, the monitoring programme offers an early indication for corrective actions.

During the operational phase, various data, such as meteorological, geological, hydrological and geochemical parameters, are collected. A periodic monitoring of all relevant parameters allows the detection of any change that may occur. Water quality is monitored during the operation of waste disposal facilities. Groundwater and surface water at and around the disposal facility site are monitored to detect radioactive materials above the baseline levels. Additionally, the direction, rate and velocity of water flow around the site are periodically updated. Soils, crops and animals are also tested for changes in the levels of radioactive materials present [5.3].

In the early operational stages of the facility, frequent and detailed environmental measurements are necessary to confirm the prediction of the behaviour and transfer of radionuclides to the environment. Any decision to change the frequency of sampling or the scope of the environmental monitoring programme should be reviewed carefully to cover changing discharge area or unexpected releases, as well as any existing concerns raised by the public.

5.2.1.3. Post-operational phase

The post-operational phase begins when the radioactive waste disposal facility is closed and no longer accepts waste. The monitoring programme must be continued for a certain time period after the facility's closure, and it should be continued for as long as required by the host community to provide public confidence, or to ensure that the predicted integrity of the disposal facility is maintained.

After the closure of the disposal facility, groundwater is the likely route for migration of radioactive materials from the disposal site. As a result, monitoring activities concentrate on groundwater during the post-operational phase. Air, soil and vegetation are monitored as well. The data collected during this phase are compared with the information collected during the pre-operational and operational phases.

Monitoring programmes should be designed and implemented to maintain the overall level of safety of the facility after closure. Monitoring during the post-operational phase should provide the assurance of post-closure safety. The IAEA has indicated that the monitoring programme relating to the post-closure safety of the geological disposal facilities should be planned before construction of the geological facility [5.5]. The programme aims to provide assurance of post-closure safety, but it should also remain flexible. If necessary, it needs to be revised and updated during the development and operation of the facility. Once the repository is closed, monitoring should be restricted in general.

5.2.2. Periodic review

Generally, all monitoring programmes should be subject to periodic review to ensure that measurements continue to be relevant for their purposes. Monitoring programmes should be reviewed to make sure that no significant route of discharge or exposure pathway has been overlooked. In case of changes in the manner of operation of the facilities or in the nature of the discharges, the monitoring programmes should be re-evaluated to ensure their continuing validity. The facility and/or the monitoring bodies should consider involving the public in designing and reviewing monitoring programmes to help eliminate any concerns raised. In addition, the monitoring programme is expected to be revised periodically in response to technological development in equipment, modifications of the repository design and changing social demands.

5.2.3. Key issues and relevant parameters

In general, monitoring programmes contain many common issues, as discussed by the IAEA [5.1]. They include degradation processes from construction, the behaviour of waste packages, chemical interactions near field and in the surrounding geosphere and possible releases of radioactive substances.

5.2.3.1. Degradation processes from the construction of the repository

A number of processes are expected to occur in response to the construction of a geological repository. During construction, the excavated space filled with air at atmospheric pressure is a significant perturbation to the natural condition of the geological environment. In terms of hydrology at depth, inflow of water continues and causes complete saturation of the backfilled repository. In general, the inflow can cause a change in groundwater geochemistry. For example, exposure to atmospheric oxygen and CO_2 in a repository and possible infiltration of shallow meteoric groundwater causes carbonation and oxidation of the groundwater, as well as the decrease in pressure to degassing of other gases, like methane [5.6].

5.2.3.2. Behaviour of the waste package and its associated buffer material

The evolution processes of the engineered barrier system and the migration processes of substances within it are important items in the monitoring programme, because they are closely related to the performance of the engineered barrier system. Some processes, such as the swelling of bentonite, are required to fulfil the performance requirements of the engineered barriers [5.7]. Observing the behaviour of the waste package and the engineered barrier system is a necessary part of monitoring.

Monitoring activity for the transfer of heat generated by the spent fuel is important to secure the performance of the engineered barrier system. The thermal expansion of the rock increases mechanical stress and causes the deformation of the wall of deposition holes, where heating is the most intense. Moreover, temperature is a crucial factor in geochemical processes. The development of the temperature field depends on the heat produced from each canister, the repository layout and the capability of various components to conduct heat into the surrounding rock mass [5.8].

5.2.3.3. Near field chemical interactions between introduced materials, groundwater and host rock

Hydrogeochemical conditions are an important aspect to consider for the durability of the engineered barriers and for the solubility and migration of radionuclides. Engineered barriers include the canister, bentonite buffer, deposition tunnel backfill and auxiliary components, such as plugs, seals and backfill of other excavated spaces. The goal of monitoring engineered barriers is to produce useful information for long term analyses and simulations of their behaviour and evolution.

Engineered barrier system evolution and migration processes are included in the monitoring programme, in general. The degradation of engineered barrier system components comprises a variety of issues, which should be covered by the monitoring programme. Water uptake into the buffer and backfill is one of the key processes affecting the performance of the engineered barriers, especially among those processes that are expected to occur during the operational period.

Mineralogical alteration within the bentonite buffer and tunnel backfill can safely be assumed to occur too slowly to be detected within any conceivable monitoring period. Meanwhile, water uptake and the resulting swelling are essential processes that affect the barrier system at times scales for which monitoring is possible. The deposition tunnel plugs are special among the components of the engineered barrier system, because they remain exposed and accessible along the central tunnels for years after installation. Thus, the plugs will be readily available for direct long term monitoring. The physical condition and stability of the plugs provide direct information on achieving their performance targets during the operational phase.

Currently, the presented targets are considered possible to monitor continuously in a demonstration facility or in actual deposition tunnels. These processes include the corrosion of the copper overpack and deposition of material onto it, chemical changes in buffer and backfill materials and corrosion of steel in tunnel plugs.

The chemistry of groundwater around the repository and within the engineered barrier system is influenced by foreign materials that, although not belonging to the engineered barriers, are introduced into the repository, either on purpose or inadvertently. The amounts of foreign materials, such as cementitious materials, additives, explosives, organic materials, metallic support bolts, etc., should be monitored in the monitoring programme. During the construction and operation of the repository, several types of foreign materials are used, mainly for engineering purposes. These foreign materials are not part of the engineered multibarrier system (e.g. copper canister, bentonite) or the natural environment (e.g. bedrock and groundwater). When the repository is closed, those foreign materials are usually removed. Monitoring of foreign materials should be continued during the operational phase.

The migration of radionuclides is also a crucial issue for the safety of the repository within the near field. In addition, the presence and mobility of other substances that facilitate the corrosion of a canister are important to monitor. Most migration processes can occur in all components of the engineered barrier system. In general, most released radionuclides are effectively retained by sorption on solid surfaces, precipitation and co precipitation. It is also conceivable that gas phases cause gas transport, which can either facilitate or inhibit the migration of radionuclides or other significant substances. Colloid mediated transport occurs as a consequence of excessive flow of groundwater in contact with bentonite. Processes occurring inside the copper canister are difficult to monitor, because the overpack must be kept intact. Moreover, it is reasonable to assume that few canisters will be breached within 100 years; thus, the migration processes starting after the loss of canister can be ignored in the monitoring programme. According to assumptions, heat generation from radioactive decay is the only canister process relevant to the monitoring programme.

5.2.3.4. *Chemical and physical changes in the surrounding geosphere*

Geochemical and physical changes in the surrounding geosphere are closely related to the target properties of a host rock. A significant part of the processes and target properties of a host rock concerns the chemical compositions of groundwater. It is evident that hydrogeochemical monitoring must continue to have an important and well defined role in the programme. Relevant chemical characteristics to be monitored include processes like chemical rock-water interaction, such as concentrations of various ions and major geochemical elements.

To understand the physical changes in the surrounding geosphere, a monitoring programme concentrates on the assessment of potential tectonic movements and the stability of the bedrock, although the construction of a repository is not expected to induce a large scale movement of the bedrock block. However, the evaluation of any tectonic event or possible instabilities is important for the safety assessment.

5.2.3.5. *Monitoring of releases of radioactive substances in the environment of a repository*

In order to fulfil the legal responsibility in the operational phase of a repository, it is necessary to establish the baseline of natural radiation and concentrations of important radionuclides in the environment during the pre-operational and operational phases. It should be noted that this programme does not cover radiation monitoring within the disposal facility. The protection of personnel from any radiation hazard is an issue of occupational safety. From the point of view of long term safety, it is necessary to monitor the migration and effect of radionuclides in the biosphere. They are considered significant for modelling radionuclide migration and calculating the exposure of humans and animals to radiation.

5.2.4. Monitoring methods

5.2.4.1. *Rock mechanics*

Monitoring rock mechanics includes continuous microseismic measurements [5.9], measurement of relative movement of bedrock blocks by GPS [5.10], electronic distance, precise levelling techniques [5.11], as well as extensometer, temperature and convergence measurements in excavated spaces [5.12]. In programmes for seismic monitoring, GPS measurements and precise levelling should continue during the construction of a repository. The extension of networks for monitoring methods is needed to cover the operational volume, both on the surface and underground. The programme for rock displacement (extensometer, convergence), fracture/fracture zone displacement, load cell, temperature and visual tunnel monitoring needs to be continued during the operational phase.

5.2.4.2. *Hydrology and hydrogeology*

Hydrological monitoring is based on groundwater pressure and flow measurements in deep and shallow boreholes drilled in bedrock, wells and groundwater tubes in the overburden and measurement weirs in a disposal site. The main expected hydrological effect of the construction of a repository is changes in hydraulic pressure [5.13[, [5.14], [5.15]. The construction of underground facilities causes leakages of groundwater into the tunnels. Leakages cause disturbances to pressure head and flow conditions around a repository.

Disturbances in hydrology also cause changes in hydrochemical conditions, such as an intrusion of saline water along local fractures or zones into the repository level.

In many cases, hydrological monitoring is carried out in selected drill holes. The network of selected boreholes needs to be developed again for the new phase of the project. Fracture properties within the hydraulic network in terms of hydraulic conductivity or transmissivity are measured by using the Posiva Flow Log (PFL) [5.16] and by the Hydraulic Testing Unit (HTU) [5.17] in deep drill holes, and using the slug test method [5.18] in shallow boreholes. The Posiva Flow Log tool is applied to measure flow conditions as well as saline groundwater distribution (electrical conductivity). In addition, groundwater salinity is measured by groundwater sampling and indirectly by geophysical Gefinex 400S (SAMPO) measurements [5.19].

In a completed borehole, geophysical loggings, such as radiometric, electric, magnetic and acoustic methods, can be performed, as well as radar and seismic surveys, depending on the investigation targets. After the geophysical logging, the borehole wall is videotaped using the Borehole Image Processing (BIP) system [5.20]. For example, the borehole radar is a useful tool for locating and determining the orientation of local major and minor fracture zones and dikes from a borehole. Seismic methods are usually used to locate similar structures at even greater distances, although they have poorer resolution. Vertical seismic profiling is an effective method in connection with seismic reflection surveys to indicate the occurrence and extent of major fracture zones in a relatively large rock volume [5.21]. Through multiple applications of these methods with different ranges and resolutions, the results become more reliable and accurate. In addition, the methods identify different properties of the rock, such as electrical and mechanical, respectively [5.21].

5.2.4.3. Evolution of groundwater flow

For a long period of monitoring, the groundwater table level enables a good basis for the assessment of possible changes in the evolution of groundwater table. The groundwater table level is monitored with groundwater observation tubes and shallow drill holes. Changes in flow conditions provide information on hydraulic connections between the drill holes and the tunnels. Changes in the direction of flow cause geochemical changes in the groundwater composition. Flow conditions in open drill holes are monitored by difference flow logging measurements (PFL DIFF). Cross-drill hole flow is measured by a transverse flow meter (PFL TRANS).

5.2.4.4. Evolution of hydraulic network and fracture properties

The study of the evolution of hydraulic properties in the bedrock (hydraulic network and fracture properties) is based on long term monitoring in packed-off drill holes and different types of hydraulic measurements (Posiva Flow Log, Hydraulic Testing Unit and slug tests). In general, hydrological and hydrogeological monitoring continues during the operation of a repository with the same programme as before the operation. The programme can be revised, if necessary, based on the results from data collected before the operation. The focus of the drill hole measurements (difference in flow and cross flow measurement, as well as hydraulic conductivity) is in the areas where the construction of repository tunnels is located. The packed-off sections in the drill holes are planned to cover the areas assumed to be influenced by the construction.

5.2.4.5. Evolution of hydrogeochemical characteristics of groundwater

Hydrogeochemical monitoring includes regular groundwater samplings from selected sampling locations, such as drill holes, groundwater stations, groundwater observation tubes, etc. The results of monitoring contribute to the detection of possible changes in chemistry due to the construction of the repository. The selection of sampling locations varies for each stage of the repository development.

In general, the chemistry of shallow groundwater is monitored by regularly analysing basic chemistry and isotopes from groundwater samples from yearly selected groundwater observation tubes and shallow drill holes. The groundwater sampling method from a deep drill hole on the surface depends on whether the drill hole is open or packed off. For example, in a multi packered drill hole, samples have been collected using various methods, such as a Vesitin pump, while in an open drill hole, pressurized water sampling equipment is used [5.22]. The pressurized water sampling equipment collects dissolved gases and microbial samples in situ. In addition, a new sampling tool has been developed for sampling in situ water along a targeted fracture.

The evolution of deep and shallow groundwater should be studied for a long period of time. The most critical chemical parameters in groundwater with regard to long term safety are salinity, pH, and oxygen and dissolved sulphide concentrations [5.23]. In general, the monitoring of hydrogeochemistry should be continued before and during the operational phase.

5.2.4.6. Monitoring programme for the biosphere

Monitoring of the surface environment focuses on forest ecosystems (biosphere). The major concern of the monitoring programme is to generate data for biosphere modelling applied in the safety assessment and to establish the baseline for the monitoring of radioactivity in the environment.

For surface monitoring, water and soil samples are collected in priority areas and analysed in the laboratory for chemical, geological, hydrological and biological compositions. Sample series are collected over a long period of time to see their patterns over time. Data on precipitation, temperature, air pressure, snow depth, drainage basins and stream flows are acquired either from recordings in the vicinity or by measuring these parameters. Monitoring atmospheric conditions includes direct meteorological parameters, such as temperature, precipitation, snow depth and ground frost, primarily needed when modelling surface and near surface hydrological conditions. Meteorological observations are also needed to determine the dispersion of releases into the air in various other modelling and data interpretation tasks. It is necessary to perform soil solution sampling for determining the chemical composition and the amount of percolating water.

The infiltration of groundwater and land uplift are processes related to the evolution of the geosphere affecting long term safety. Monitoring related to the biosphere generates data that requires long timescales or other extensive studies for biosphere assessment. To complement the information gained on the vertical movements of the bedrock within the rock mechanics monitoring programme, laser scanning of the ground surface elevation can be a useful tool for the surface environment programme. The interaction between the surface environment and the groundwater in the bedrock is related to the infiltration, and the discharge of the groundwater is controlled by the water balance of the overburden and the vegetation.

5.2.4.7. Engineered barrier system

For monitoring purposes, the canister can be divided into several areas of interest. The main components are the copper canister, cast iron insert and heating elements which represent fuel rods. The overall temperature distribution is measured by using temperature sensors at many locations of each component. The purpose of temperature monitoring is to investigate the possible thermal induced effects, such as movement, strain and deflection.

The movement of components can be measured with different types of deflection transducers and strains by strain gauges and optical fibres. The overall movement and deformation of the canister can be analysed with inclinometers and displacement sensors.

5.3. MONITORING OF CARBON DIOXIDE DISPOSAL

Monitoring plays an important role in qualifying and quantifying the risks involved in underground CO_2 disposal to ensure that it is safe, effective and acceptable. The purposes of monitoring are to assure the safety of the facility, and that there are no local environmental problems or CO_2 leakage into the atmosphere. These requirements provide a framework for monitoring programmes. To ensure the safe and effective disposal of CO_2, it is important to understand the reservoir properties and the nature of how the injected CO_2 spreads and interacts with the rock matrix and reservoir fluids. The monitoring programme is aimed to observe the physical and chemical effects of the CO_2 injection on the state of the reservoir system. In addition, the chemical reactions that form the predicted mechanisms for long term disposal of CO_2 within the reservoir are evaluated throughout the programme.

Monitoring also observes the dynamic response of the reservoir to CO_2 injection and plume movement within and outside of disposal areas. Additionally, the injection of CO_2 should be monitored to control injection well completion, injection rates and wellhead and formation pressures. After the injection of CO_2, the monitoring programme should be continued to ensure the CO_2 remains trapped and does not leak out of the intended disposal reservoirs. For the monitoring programme, simulations are also important to test and improve geologically based simulator predictions of how the CO_2 flood will progress. Field monitoring methods over a wide range of scales are applied to monitor subsurface CO_2 movement and associated *in situ* stress variations during the injection process. Monitoring methods have been evaluated to establish the underlying basis for the sensitivity of these methods to CO_2 induced subsurface changes. Ultimately, the comparison is made between the monitoring results and reservoir simulations in order to improve the accuracy of reservoir simulations and verify the monitoring results.

5.3.1. CO_2 disposal phases and related monitoring

The purposes of monitoring are different for each phase of a CO_2 disposal project. Monitoring is required as a part of the licensing process for underground CO_2 injection. It is also used for a number of purposes, such as tracking the location of the plume of injected CO_2, ensuring that CO_2 is not leaking, and verifying the quantity of CO_2 injection. The concept of three distinct phases in the life cycle of a CO_2 disposal project was introduced by Benson et al. [5.24]. Monitoring activities vary across these phases that are defined as follows.

5.3.1.1. Pre-operational phase

In the pre-operational phase, the project design is carried out and baseline conditions are established. During this phase of the project, the geology of the site is characterized. The primary purposes for monitoring are to obtain baseline data and to assess the integrity of shut-in, plugged or abandoned wells. Additionally, the disposal efficiency and processes are identified and confirmed.

5.3.1.2. Operational phase

During the operational phase, CO_2 is injected into the disposal reservoir, which is expected to take place over a period of 30 to 50 years. During CO_2 injection, surface facilities and injection rates are monitored. Additionally, the location of the plume is tracked and other monitoring activities are conducted, as required by the regulatory permit.

5.3.1.3. Post-closure phase

After CO_2 injection, the wells are abandoned and plugged. Equipment and facilities are removed, and site restoration is accomplished. Only the necessary monitoring equipment is retained in the post-closure phase. During this period, results from monitoring are used to demonstrate that the disposal project is performing as predicted by modelling, and that it is safe to decrease or discontinue further monitoring. The duration of the closure phase varies, depending on factors such as the regulatory requirements and the expected level of project performance. The post-closure phase could last from several decades up to several centuries. A limited monitoring programme over several decades may be sufficient to demonstrate that the CO_2 will remain safely underground and that monitoring is no longer required. However, a disposal project in a very large saline formation, where CO_2 may continue to migrate even after injection, may require hundreds of years to demonstrate that the project is performing as expected and that the CO_2 is safely contained.

Once it is satisfactorily demonstrated that the site is stable, monitoring is no longer required, except in the event of leakage, legal disputes or other matters that may require new information about the status of the disposal project, such as other ongoing environmental impacts.

5.3.2. Key issues and relevant parameters

5.3.2.1. Establishing baseline condition

CO_2 is everywhere in the air, water and soils. The concentrations of CO_2 in these media vary on daily, seasonal or longer periods of time, depending on the sources, sinks and long term processes. It is important to have a well defined baseline for CO_2 concentrations, although it is not an easy task to carry out. Many of the parameters that can be used to monitor a CO_2 disposal project are not directly indicative of the presence of CO_2, but the changes in these parameters over time and their reaction products can be used to detect and track its migration. For these reasons, the baseline should be established not only from the average value of these parameters, but also from the variation in space and time before the project begins. This time lapse approach is the foundation for monitoring CO_2 disposal projects. Without an adequate baseline, it is impossible to separate disposal related changes in the environment from the natural spatial and temporal variations in the monitoring parameters. For most disposal projects, the monitoring baseline is obtained during the pre-operational phase.

5.3.2.2. Effective injection controls

To ensure effective injection well controls, it is critical to monitor the condition of the injection well by measuring injection rates, wellhead pressures and formation pressures. For example, if the injection pressure is too high, injection is known to cause seismic events created by micro-fracturing the reservoir rock or by small movement along existing fracture surfaces.

5.3.2.3. Detecting leakage

Previous experience from CO_2 disposal and injection of liquid wastes into deep geological formations has shown that shut in, plugged or abandoned wells that are ineffectively sealed are the most probable leakage pathways [5.25]. Therefore, at disposal sites with old and abandoned wells, monitoring is needed to verify these wells do not provide any leakage pathway from the deep and shallow subsurface. Pre-injection testing should be completed before a CO_2 disposal project is initiated if the locations of the abandoned wells are identified.

Monitoring is needed to track the location of the CO_2 plume as a supercritical fluid or gas in the subsurface. This is fundamental for ensuring that the CO_2 remains in the disposal reservoir. Monitoring is also needed to detect leakage and leakage pathways. If there is evidence that significant leakage has occurred from the disposal formation and CO_2 has migrated to the land surface or ocean floor, monitoring methods to detect the location of seepage and the concentration and flux of CO_2 are needed. Monitoring methods to detect and quantify seepage are different, depending on the location of the disposal site. For example, at onshore disposal sites, seepage monitoring requires a combination of soil gas CO_2 concentration measurements, CO_2 concentrations in air and surface flux measurements using eddy flux towers or flux chambers. On the other hand, for offshore sites, detecting and monitoring seepage to the ocean floor require a combination of measurements, including ocean water chemistry, the detection of hydrate formation and other factors. If significant leakage occurs, monitoring is needed to assess the consequent environmental impacts, including groundwater contamination and possible human health impacts.

5.3.2.4. Disposal efficiency and processes

Geological disposal uses four processes to keep CO_2 from returning from the atmosphere: (1) physical trapping (or hydrodynamic trapping) below a low permeable caprock, (2) residual gas trapping, (3) dissolution into the in situ reservoir fluids (solubility and ionic trapping) and (4) conversion to minerals that become part of the reservoir itself (mineral trapping) [5.26]. The dominance of these mechanisms changes over time, based on the evolution from physical trapping and residual gas trapping, to solubility trapping and, finally, to mineral trapping. The timescale and degree of evolution vary depending on the condition of the disposal site, such as the type of formation used for disposal and the fluids in the formation. In many cases, physical trapping may be the most important process to monitor.

5.3.2.5. Comparing model predictions with monitoring measurements

One of the most important purposes of monitoring is to confirm that the project is performing as predicted by modelling. The comparison between modelling and monitoring validates that the disposal project performs as anticipated. This is particularly valuable in the early stages of a project, when there is an opportunity to alter the project. Moreover, monitoring data collected early in the project is often used to refine and calibrate the predictive model further. The refined model then forms the basis of predicting the longer term performance of the project [5.27], [5.28].

5.3.3. Monitoring methods

The monitoring programme aims to detect the responses of the reservoir as CO_2 is injected. Baseline characterization of the reservoir, such as porosity, permeability, fracture systems and fluid distribution prior to injection, is important to plan the monitoring of the CO_2 plume and anticipating processes. In addition, baseline measurements provide the reference with which all subsequent monitoring surveys can be compared. After CO_2 injection, the goal of monitoring is to track the saturation and distribution of CO_2 within the reservoir. The interaction of the CO_2 with other reservoir fluids is monitored to determine pressure variations and identify off-trend flow so that the injection process can be adjusted accordingly. Consequently, monitoring ensures the security of CO_2 within the reservoir. Finally, monitoring provides a means of verifying the volume of CO_2 that resides within the reservoir. Efficient and complete access to the reservoir volume and avoidance of premature flow through of CO_2 to producing wells is important.

5.3.3.1. Modelling

Initial predictions of CO_2 plume movements are based on flow simulations using a reservoir model based on a dense network of wells in the CO_2 disposal site. A variety of seismic and geochemical sampling methods are subsequently used to monitor the CO_2 injection process and characterize the response of the reservoir between monitoring boreholes. Models, such as numerical reservoir flow simulations and geochemical simulations, can predict several reservoir attributes, including fluid pressure, reservoir production and injection rates. Information used for calibration and performance confirmation include downhole pressure, actual injection and production rates, 3-D seismic data, tracer data (reservoir and near surface), geophysical logging data, geochemical data from cores and reservoir fluid test data. An evaluation of environmental and safety related factors is completed based on the results from geo-mechanical modelling [5.29].

5.3.3.2. Atmospheric monitoring

For any geological CO_2 disposal project, it is necessary to identify CO_2 leakage long before it reaches the surface. Geologically disposed CO_2 encounters multiple barriers in its flow path. CO_2 leakage from a disposal reservoir may create significant CO_2 fluxes at the surface. The magnitude of CO_2 leakage fluxes depend on a variety of factors, such as the mechanism of emission, wind and density driven atmospheric dispersion. Anomalous surface CO_2 fluxes may be detected using several techniques, such as CO_2 detectors, laser systems, Eddy covariance, etc. [5.24].

5.3.3.3. Soil gas and vadose zone monitoring

Near surface geochemistry methods can be used to detect short term rapid loss or long term intermittent leakage of CO_2 from gas disposal formations. These techniques are routinely employed in the environmental industry and include the monitoring of soil gas and shallow groundwater. In general, both consist of purging the monitoring point and collecting a sample, followed by analysis and interpretation. Soil gas collection is performed to measure the natural background concentrations and to check any leakage of CO_2 or associated tracer gases as the direct result of the solvent plume occurring at the disposal site.

The use of magnetometers is a possible near surface geophysical technique. Magnetometers measure the strength and/or direction of the magnetic field in the vicinity of the instrument. In an effort to develop comprehensive monitoring techniques to verify the integrity of CO_2 reservoirs, airborne and ground based magnetometry, in conjunction with methane detection, can be used to locate abandoned wells that can be a source of leakage from a potential CO_2 disposal reservoir. Magnetotelluric surveys (soundings) are a natural source electromagnetic geophysical method that utilizes variations in the Earth's magnetic field to image subsurface structures [5.30].

5.3.3.4. Geochemistry of production fluids and gases

The methodology employed in the geochemical monitoring phase of the project is to sample produced fluids before and during the injection of CO_2. Samples of produced brines, gas and oil need to be collected and analysed. The monitoring provides changes in the chemical and isotopic parameters to interpret the chemical processes in a disposal reservoir as a result of CO_2 injection. The geochemistry of produced fluids and gases has also been monitored and analysed for chemical and isotopic parameters to track the path of injected CO_2.

As CO_2 is injected into the reservoir, a number of important processes are expected to occur, including CO_2 dissolution, carbonate mineral dissolution and, eventually, carbonate precipitation in the form of calcite or other carbonate minerals. Observing the resultant variations in calcium and magnesium concentrations, total alkalinity, pH and carbon isotope ratios in the produced fluids and gases provides a measure of the degree of interaction taking place between reservoir fluids, injected CO_2 and reservoir rocks [5.6].

5.3.3.5. Seismic methods

The injection of CO_2 into a reservoir affects its seismic properties through a number of mechanisms. In the saturated porous rock, the seismic characteristics of the rock are generally controlled by the characteristics of the rock matrix, including matrix stiffness, density and porosity. The injection of CO_2 modifies both the pore fluid and the pore pressure within the rock. Thus, it should change the associated seismic properties.

The fluid with a smaller range in density has a secondary effect on the seismic properties. Thus, the observable variations in the seismic properties of a reservoir are apparent in regions where the molar per cent of CO_2 exceeds 40% [5.31]. The displacement of oil by water results in significant changes in seismic properties. The implication of this behaviour causes the seismic measurements to be highly sensitive to reservoir situations where a CO_2 rich phase exists. This sensitivity of the seismic reflection response to gas is well known [5.31]. The characteristics of reservoir rock core samples provide the primary source of information to determine the effects of the CO_2 plume on the seismic properties of a disposal site. The properties of rock cores can also be used for modelling. A common rock physics model [5.32] is applied to predict seismic changes over the broader range of porosities observed in the reservoir.

A variety of seismic imaging methods have been applied to monitor the CO_2 plume. In each case, baseline data are collected prior to the start of the CO_2 plume movement to provide a reference for comparison. Subsequently, the monitoring of seismic data is required during the first two years of the CO_2 flood to determine changes in the seismic properties of the reservoir relative to the baseline measurements.

This methodology is commonly referred to as time lapse imaging, or in the case of 3-D seismic data, 4-D imaging, where time represents the fourth dimension. Time lapse seismic data include: 1) surface 3-D 3-component seismic reflection surveys for the entire area, 2) surface 3-D 9-component seismic reflection surveys for 4-patterns within the area and 3) 3-D 3-component vertical seismic profiles (VSP) for a single well within the area. In addition, horizontal and vertical cross-well tomography surveys and vertical seismic profiles can be used. Single or multi component 2-D and 3-D surface seismic surveys are widely deployed technologies in oil and gas exploration that utilize surface sources to generate downward propagating elastic waves that are reflected from subsurface features and return to the surface, where they are recorded by ground motion sensors (geophones). In the case of a 3-D survey, a regular 2-D grid of surface sources and sensors is deployed. The data recorded in this manner is combined to produce a 2-D or 3-D image of the subsurface [5.9]. VSP techniques provide seismic measurements that obtain high resolution images near a borehole [5.10]. VSP techniques utilize sensors deployed within a borehole and sources located at the surface, whereas crosswell tomography uses sources and receivers both deployed in boreholes. The advantage of VSP, crosswell seismic and other high resolution methods is to obtain more precise estimations of the CO_2 induced effects on seismic properties.

One of the disadvantages of seismic techniques is the difficulty of quantifying the amount of CO_2. It will be possible to quantify leakage rates only by combining geophysical measurements with other techniques, such as formation pressure measurements and reservoir simulation [5.11], [5.12]. For a more accurate estimation, additional researches and field tests are required.

Pre-injection seismic measurements

The geological horizons are identified in this data set, generated from pre-injection seismic measurements and the subsequent monitoring surveys. In general, the top of the reservoir horizon is indicated, along with several other horizons of interest. The identification of the various geological horizons with seismic events is based on the correlation of the seismic data with well log generated synthetic seismic data.

Time lapse seismic measurements

The seismic survey provides an initial baseline measurement that can be compared to subsequent seismic surveys to create a time lapse image of CO_2 plume migration. The amplitude differences are most prominent at the reservoir level and beneath. The large differences below the reservoir are most likely artefacts, as they are a result of the time delay introduced by changes at the reservoir level that produce misalignment of the baseline and monitor waveforms everywhere beneath. Significant time delay anomalies are readily apparent around the horizontal injection wells [5.33]. The delay time represents the cumulative travel time delay due to CO_2 effects at the overlying reservoir level. Sometimes the small thickness of the reservoir can be missed through time lapse seismic measurements. Minimum fractional velocity changes determined from the travel time delays to complete the reservoir thickness show values of up to about 10% [5.11]. Fractional velocity decreases may actually be greater if the CO_2 is restricted to a subinterval of the reservoir.

Passive seismic monitoring

Micro-seismic (passive seismic) monitoring is performed to monitor the dynamic response of the reservoir rock matrix to CO_2 injection and assess the level of induced seismicity in regard to safety of existing surface infrastructure. Microseismic monitoring can be used as an alternative means of mapping the spread of CO_2 within the reservoir [5.15].Passive seismic monitoring is performed using a seismic array installed close to the reservoir and cemented as part of the normal well abandonment. An array consists of several geophones and it is mounted in a vertical well. This method is used to monitor CO_2 injection at close proximity to the array. Background seismicity is recorded with the array prior to the CO_2 injection.

Seismic sensitivity to the physical effects of CO_2 injection

An objective of the monitoring programme is to track and quantify the distribution of CO_2 in the subsurface over time by using seismic techniques. A miscible flood, brine and oil within the reservoir are partially replaced by pure CO_2, a CO_2 rich phase or an oil rich phase. CO_2 can also dissolve in the brine. Its solubility in brine is very low (~1–2% molar fraction) as compared to its solubility in oil. The pore fluid is partially replaced by fluids containing a large molar fraction of CO_2. Thus, if it can be demonstrated that the seismic response is sensitive to either oil or water being replaced by fluid phases with large fractional CO_2, then the seismic images should be a proxy for the distribution of CO_2 in the reservoir. The seismic detection limits to monitor the injected CO_2 volume depend on various factors, including the porosity and fluid saturation of the injection formation. The repeatability of the seismic measurements determined by noise, surface recording conditions, and the frequency content of the seismic wavelet, and the seismic wave speed of the subsurface are additional factors.

Electrical resistance tomography is a technique of imaging subsurface electrical conductivity. This method, deployed in time lapse mode, is capable of detecting conductivity changes caused by the injection and movement of CO_2. This method utilizes borehole casings as electrodes for stimulating electrical current in the ground and measuring the electrical potentials that are induced [5.30].

High precision gravity (microgravity) surveys are a near surface geophysical technique used to detect changes in subsurface density [5.30]. The densities of CO_2, typical reservoir fluids and their mixtures are known or can be obtained by geochemical sampling. For most of the depth interval for disposal, CO_2 is less dense and more compressible than brine or oil, so gravity (and seismic) methods are candidates for brine or oil bearing formations.

5.4. COMPARATIVE ASSESSMENT

Monitoring is an important part of developing and operating a radioactive waste or a CO_2 disposal project, starting from the initial baseline data collection and continuing through to the closure and sealing of the disposal site, and possibly even longer. In both areas, one of the major purposes of monitoring is to ensure that the sites are not leaking and are behaving as predicted from modelling. There are some general lessons to be learnt from a broad range of experiences in both radioactive waste and CO_2 disposal that should be useful for both, although the types of monitoring carried out in the two areas are not always directly applicable to each other. For effective monitoring, a range of standard protocols reflecting the regulations is needed. Environmental monitoring likely becomes less important with time as retention processes become more important. However, the decision on when to start and cease monitoring should be based on prevailing regulation in both radioactive waste and CO_2 disposals.

Important issues regarding the monitoring programme start with the need to collect the adequate baseline data that are representative of the undisturbed site and to create public confidence. In order to achieve the goals of monitoring, it is crucial to obtain near surface, surface and underground measurements using a variety of ecological, chemical and physical parameters. Subsequent operational and post-operational monitoring data can then provide meaningful inputs to assessments.

In the case of radioactive waste, the production of heat by radioactive waste can initially affect the environment of a repository. Any radionuclide released from the waste containers technically act as trace contaminants. Radionuclides do not significantly affect the evolution of the system. On the other hand, the engineered barrier system employed in a radioactive waste repository significantly modifies the surrounding geological environment. The actual environmental changes depend on the particular repository design that reflects the nature of radioactive wastes. Thus, the objectives of a monitoring programme related to a radioactive waste repository give a significant priority to the near field of waste containers and the geosphere, as well as radionuclides.

In contrast, a CO_2 disposal project relies on the integrity of the geological environment for containment, and the leakage of CO_2 is a major issue to be tested during the early post-closure phase. Additionally, CO_2 injection alters the geological environment, such as micro-seismic events and geochemical changes. The physical form of the CO_2 varies with depths [5.34]. Consequently, it is important to develop protocols to monitor environmental changes as the result of CO_2 leakage for the CO_2 disposal site, while the environmental changes caused by the multibarrier system should be monitored for a radioactive waste disposal site.

In general, surface monitoring in a radioactive waste disposal repository is relatively less important compared to CO_2 disposal soon after the closure and during the post-operational phase, because the release of radionuclides from the repository is unlikely due to the engineered barrier system. However, in the case of CO_2 disposal, the integrity of the geological containment of CO_2 needs to be tested soon after the closure, because there are no engineered barriers.

The detailed pre-operational monitoring and characterization of baseline condition are prerequisites in both areas. In the case of radioactive waste disposal, the geosphere surrounding a repository can comprise an integral part of the barrier system utilized to minimize radionuclide migration. In the case of CO_2 disposal, geological features (for example, caprock and sealed fractures) provide barriers to CO_2 migration. During the pre-operational phase, some monitoring techniques that are used to characterize the baseline condition at a disposal site for radioactive waste disposal are similar to those used for a CO_2 disposal reservoir, e.g. a variety of seismic survey techniques, borehole studies for geological and hydrogeological data and geochemical analyses. These techniques are useful, not only to understand a disposal site for CO_2 disposal, but also to assure effective CO_2 disposal when it extends into the operational and post-operational phases.

There are significant differences in monitoring approaches in both areas. In the case of radioactive waste, the underground environment hosting the waste is accessible via shafts, tunnels or drifts. Thus, the near field in which radioactive waste is to be stored is relatively well characterized, even if uncertainties exist in the surrounding fields. Detailed near field rock characterization is possible, because this volume has been excavated and accessible in situ during the construction and operational phases of the project. However, additional barriers are added to the excavated volume to provide a multibarrier engineered system for waste containment.

For CO_2 disposal projects, in contrast, the amount of information from monitoring is much sparser, limited to a few boreholes and indirect methods, such as seismic surveys, with no direct access. For example, the underground disposal of CO_2 relies on the intrinsic disposal capacity of the host rock with its natural porosity and permeability, rather than in an excavated cavern.

For radioactive waste, the engineered barriers will inevitably become less effective with time, therefore safety assessment calculations have to consider the return of some radionuclides to the surface environment, possibly in extremely low concentrations over very long timescales. This might require long term monitoring to ensure the safety of the repository. While the probability of radionuclides returning to the environment is almost zero, this is not the case for CO_2 without engineered near field barriers. In the case of CO_2 disposal, wells of various types more likely result in the leakage of CO_2 to the environment compared to the radioactive waste disposal. Thus, understanding the potential impact of wells is one of the key issues for the geological disposal of CO_2 [5.35].

In the case of radioactive waste disposal, the relatively low volume of waste is managed and disposed of in relatively small facilities. In contrast, CO_2 disposal sites are numerous and mostly large scale. Consequently, CO_2 disposal projects likely face more diverse and challenging issues for monitoring to evaluate the post-operational phase, particularly in terms of environmental issues.

5.5. CONCLUSIONS

The monitoring techniques used in radioactive waste disposal are based on fundamentals of geology, hydrogeology, geochemistry, etc., which could also be applied to CO_2 disposal. The monitoring techniques in both areas can be differentiated. The parameters are measured either directly or indirectly. The direct measurement of materials in air, water or soils can be performed by using sensors, remote sensing, geochemical methods and tracers. Indirect measurement methods for targeted materials include well logs, geophysical methods (seismic, electromagnetic and gravity) and satellite and airplane based monitoring. Among these geophysical techniques, seismic methods are by far the most highly developed and can cover a large area with a high resolution. Various research programmes are being performed to optimize existing monitoring techniques. While improvements can be made and are expected in all of these areas, today’s technology provides a good starting point.

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Chapter 6

COST ESTIMATION

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6.1. INTRODUCTION

Nuclear power and carbon dioxide (CO_2) capture and disposal (CCD) are key greenhouse gas mitigation options, which are currently under consideration in several countries. Both technologies entail long term waste management challenges, and both options are based on geological disposal. These technologies and the related economic calculations have much in common, and valuable lessons can be learnt from their intercomparison. To compare these technologies, economic, social and environmental criteria need to be selected and expressed in terms of indicators.

This chapter analyses the costs of the geological disposal of CO_2 and radioactive waste in several countries. The range of countries considered in this chapter includes those that contributed to the Coordinated Research Project as partners. Due to the lack of information on CO_2 disposal costs, only radioactive waste disposal costs were assessed for India, the Republic of Korea and Switzerland. Only CO_2 disposal costs were assessed for Cuba because the country is only considering low level radioactive waste disposal. For Lithuania, both CO_2 and radioactive waste disposal costs were assessed and compared. The costs of CO_2 and radioactive waste disposal are evaluated and compared in US cent/kW·h. This chapter also compares the characteristics and locations of disposal options for CO_2 and radioactive waste in selected countries based on a comprehensive literature review.

Several studies were conducted on the comparative assessment of costs of energy technologies. In some studies, the costs of back end technologies were assessed in terms of life cycle costs. The most comprehensive study on a comparative assessment of CO_2 and radioactive waste geological disposal costs was conducted by the International Atomic Energy Agency. Toth and Miketa [6.1] present in their report the in-depth review of costs of geological disposal of CO_2 and radioactive waste for several countries. So far only a few countries have developed geological radioactive waste and CCD projects, and there is a lack of comprehensive and comparable data on radioactive waste disposal and CO_2 disposal costs.

Some studies compare the costs of the main energy technologies to reduce GHG emissions from energy systems. The life cycle electricity costs were assessed for fossil fuel based electricity generation with carbon capture and disposal and nuclear power [6.2].

Levelized costs of electricity generation options were assessed for new power plants in 2015 and 2040, including various fossil fuels with CCD options and nuclear power. However, the costs of CO_2 and radioactive waste disposal were not distinguished in these assessments [6.3]. Levelized cost is often cited as a convenient summary measure of the overall competiveness of different generating technologies. It represents the per kilowatt-hour (kW·h) cost of building and operating a generating plant over an assumed financial life and duty cycle. Key inputs to calculating levelized costs include overnight capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs and an assumed utilization rate for each plant. There are several EU funded projects dealing with the assessment of energy technologies: EUSUSTEL [6.4], NEEDS [6.5], CASES [6.6] and PLANETS [6.7]. In these studies, advanced electricity generation technologies including fossil fuel power plants with CCD and nuclear power plants were assessed. The economic assessment of energy technologies is based on average levelized electricity generation costs. Currently, the format, content and practice of cost estimates for geological disposal of radioactive waste and CO_2 vary considerably within and across countries. The reasons are largely due to different legal requirements in different countries and to historical customs and practices.

There are no generally accepted reference values for costs of carbon disposal facilities. In the literature, the range for expected investment expenditures varies remarkably. Studies dealing with this topic show that investment costs for CO_2 disposal depend on the disposal concept, geographical location and whether the disposal facility is located offshore or onshore. According to the IPCC [6.8], these costs are between 0.5 and 8 $ per ton of CO_2 disposed of, excluding the potential revenues from enhanced oil recovery (EOR) or enhanced coal bed methane (ECBM) recovery. The IPCC report presents different estimates of disposal costs for saline aquifers for different regions of the world. For Europe, costs for onshore options are between 1.9 and 6.2 US $/t CO_2 and for offshore options from 4.7 to 12 $/t CO_2. A JRC Report [6.9] and a McKinsey and Company study [6.10] present similar cost estimates for CO_2 disposal: 4–12 EUR/tCO_2 (5.3–15.8 $/t$CO_2$) (for injection depth of 1500 m.). The POYRY ENERGY CONSULTING study [6.11] presents the range of CO_2 disposal in the UK. These costs may vary between 1 and 20 £/t CO_2 (1.6 – 31 $/t$CO_2$.).

The International Energy Agency reports [6.12] that CO_2 disposal costs in saline aquifers for Europe ranges from 10 to 25 $/t CO_2, depending on the disposal concept. The ECOFYS study [6.13] presents detailed analysis of CO_2 disposal costs for specific disposal concepts that depend on the depth of disposal. The estimated CO_2 disposal costs are in the range from 1.8 to 11.4 EUR/t CO_2.

The Global Carbon Capture and Storage Institute in Australia provides in its report an economic assessment of CCD technologies [6.14]. According to this study, the initial site finding and characterization costs present a significant risk to the project and can increase disposal costs from 3.50 to 7.50 $/t CO_2, depending on the site investigated. Reservoir properties, specifically their permeability, impact on CO_2 injectivity and the required number of injection wells. Reservoirs with high permeability can reduce disposal costs by a factor of 2, to below 5 US \$/t CO_2 compared to reservoirs with lower permeability. The costs of disposal are about 5–6 US \$/kWh.

The EU GeoCapacity project [6.15] assessing European capacity for CO_2 disposal provides assessments of the CO_2 geological disposal potential in EU Member States. The costs of CO_2 disposal range from 0.7–0.8 EUR/kWh.

Several studies on CO_2 disposal costs were conducted in the USA. The Study of the Pacific Northwest National Laboratory presents 15 \$/t CO_2 costs for CO_2 transport and disposal [6.16]. McCoy [6.17] presents an in-depth analysis of CO_2 capture and disposal costs and develops a cost model based on disposal parameters for his assessment. The sensitivity analysis indicates that the total costs range from 0.32 to 31.3 US \$/t CO_2 disposed.

In the EU, participants of the Zero Emissions Platform (ZEP) have undertaken a ground breaking study on the costs of CO_2 disposal based on new data provided exclusively by ZEP member organizations from existing pilot and planned demonstration projects. The main conclusion of the study is that CCD will be cost competitive with other sources of low carbon power plants, including on- and offshore wind, solar and nuclear plants. The costs vary significantly from € 1–7/t CO_2 (1.3–9.2 \$/tCO_2) disposed for onshore depleted oil and gas fields (DOGF) to € 6–20/t CO_2 (7.9–26.2 \$/tCO_2) for offshore saline aquifer. The cheapest disposal reservoirs (large, onshore DOGF) are also the least available ones. Although well costs are about 40–70% of total disposal costs, the wide ranges in total costs (up to a factor of 10 for a given case) are more driven by (geo) physical variations rather than by the uncertainty of cost estimates [6.18].

The Department of Energy (DOE) and the Environmental Protection Agency (EPA) of the USA [6.19], [6.20] have developed a comprehensive model for the assessment of CO_2 disposal costs for the USA [6.21]. The following disposal concepts were analysed: non-basalt saline reservoirs, depleted gas and oil reservoirs, EOR, ECBM, shale gas and basalt reservoirs. The following cost categories were assessed for disposal concepts mentioned above: geological site characterization; area of review and corrective actions; injection well construction and operation; financial responsibility; closure and post-closure care; mechanical integrity testing and monitoring. This study can be used as reference for developing approximate cost estimates for CO_2 disposal projects in other countries.

Regarding the analysis of radioactive waste disposal costs, a wide variety of approaches was investigated [6.22]. The cost studies were performed for the following radioactive waste repositories: Yucca Mountain in the USA [6.23], the final radioactive waste repository Olkiluoto and Loviisa in Finland [6.24], [6.25], [6.26], the final radioactive waste repository Forsmark in Sweden [6.27], [6.28] and Boom Clay in Belgium [6.29]. Different options were analysed in Japan [6.30], options based on the Swedish concept were assessed in the UK [6.31], and cost estimations for a multinational common repository were performed in the EU [6.32].

For the Yucca Mountain project, the total repository costs are about 96 billion \$ (in 2007 dollars). The capacity for disposal is 122 100 t HM. The detailed cost structure is presented, ranging from repository development to closure and monitoring costs. A cost study by the DOE for a low level radioactive disposal facility in Texas [6.33] estimated the total costs to be \$ 142 million (in 2007 dollars). The total costs of radioactive waste disposal repositories in Finland are about 4122 million \$ [6.23]. The disposal capacity is 5643 t of uranium. They are more than 20 times higher than for Yucca Mountain. In Sweden, total costs of radioactive waste disposal amount to 5728 million $ (capacity is about 9296 t of uranium) and are similar to Finland's estimates [6.26]. In Belgium, the costs of a deep disposal facility were assessed for the reference site (Boom Clay, beneath the Mol–Dessel nuclear zone). The total costs amount to 2035 million $ (disposal capacity is 4860 t of uranium) and are more than 50% lower than for Finland and Sweden [6.26], [6.28]. In Japan, the final disposal costs were estimated for soft and hard rocks. A total of 40,000 canisters with radioactive waste will be disposed. The average costs for both rock types are about $ 33 billion and are almost 50% lower than for Yucca Mountain. In the UK, total costs were estimated based on the Swedish repository concept (KBS-3) at approximately 9 billion $ [6.31]. The capacity of disposal amounts to about 59 200 t of uranium. The SAPPIERR II project, with the participation of 14 EU Member States, developed costs estimates for a multinational common repository. Three disposal cost assessment models were applied: the Swedish, Swiss and Finnish. The total costs according to the Swedish and Finnish cost models are approximately 9 billion EUR (11.8 billion $) and more than 10 billion EUR (13.11 Bill US $) according to the Finnish cost model [6.26]. The capacity of disposal in the SAPPIERR II project is about 59 200 t of uranium. The OECD NEA report on the harmonization of decommissioning cost estimates [6.34] has studied cost estimation practices in 12 countries and concluded that a standard reporting template needs to be developed onto which national cost estimates can be mapped for easier comparison at the national and international level.

In the framework of this CRP, a comparative analysis of radioactive waste and CO_2 geological disposal costs for several countries is presented. The case studies of Lithuania, Switzerland, Republic of Korea and India were developed to assess and compare costs of radioactive waste disposal by applying the same structure for analysis and comparison: the concept of disposal and the main costs categories are discussed. The costs of CO_2 disposal were assessed and compared for Cuba and Lithuania by applying the same methodology. The total costs of radioactive waste and CO_2 disposal were assessed and compared by applying the same units just for Lithuania. The assessments provided in this chapter are limited by contributions of CRP partners.

This chapter is organized as follows: Section 6.2 presents the cost assessment methodology, followed by country case studies in Section 6.3. A comparative assessment of disposal costs is presented in Section 6.4. The main conclusions are summarized in Section 6.5.

6.2. METHODOLOGY

The geological disposal of CO_2 and radioactive waste is the final stage in the electricity generation chain for both fossil and nuclear fuels. Both options have a positive impact on GHG emission reduction because CCD significantly reduces the amount of CO_2 vented to the atmosphere and nuclear power is a low carbon technology. The comparison of electricity generation costs for various fuel chains should include the costs of CO_2 and radioactive waste disposal.

There are several options for CO_2 geological disposal available in all the countries considered in this comparison: deep saline aquifers, depleted oil and gas fields, coal mines, etc. The location and type of the field (available knowledge and reusable infrastructure), reservoir capacity and quality are the main determinants for costs: onshore disposal is cheaper than offshore; DOGFs are cheaper than deep saline aquifers; larger reservoirs are cheaper than smaller ones and high injectivity is cheaper than poor injectivity. The regulations and legal requirements applied in the countries (see Section 8) also have an impact on costs; therefore, the comparison of costs for CO_2 disposal data between countries was presented together with technical information on the disposal site. Geological disposal can be undertaken in a number of geological formations; the most commonly studied rock types are clay, salt, hard rocks, etc. The depth at which the disposed material would be emplaced depends to a large extent on the type of formation used and the isolation capacity of the overlying formations.

The disposal of radioactive waste is possible only in deep and stable geological formations with engineered barriers. Only certain types of waste are regarded as needing geological disposal, i.e. long lived intermediate level waste (ILW), high level waste (HLW) and spent nuclear fuel (SNF). Many other types of low level waste can be safely disposed of in near surface facilities. In this chapter, the focus is on deep geological disposal.

Containment and isolation of radioactive waste is provided both by the containers into which the waste is put before being emplaced in the repository and by various additional engineered barriers and the natural barrier provided by the host rock. The disposal concept will, thus, vary with the type of geological environment under consideration, specifically the host rock, and the waste forms for disposal.

The disposal concept, depth, capacity and quality have a major impact on radioactive waste disposal costs. An important cost element in radioactive waste disposal is administration costs. Administration costs may include safeguards and security activities, regulatory infrastructure and management support costs. There are other costs included in cost estimates, such as benefits paid to the state and local entities, contingency or value added tax.

The main indicator for the comparison of radioactive waste and CO_2 disposal costs in this study is the disposal costs per unit of electricity produced. The main difference in assessing the costs is the timing of investments. In the case of CO_2 disposal, almost all investments must be completed before starting CO_2 capture from power plants except long term monitoring and site care costs, whereas investments in radioactive waste disposal can be completed after the decommissioning of the NPPs. A comparative assessment of radioactive waste and CO_2 disposal costs will be presented by applying the indicator of disposal costs per unit of electricity produced. The disposal costs per unit of waste products (radioactive waste and CO_2) will also be assessed per t HM and t CO_2 and compared between several countries.

The following four cost categories were assessed for radioactive waste disposal: (1) the costs of project administration, site exploration, repository development, site investigation costs; (2) engineering costs; (3) radioactive waste handling and disposal operation and maintenance costs; (4) site closure, post-closure and monitoring costs.

The following four cost categories were assessed for CO_2 disposal: (1) the costs of project administration, geological site characterization, area of review and corrective actions; (2) engineering costs of injection well construction; (3) well operation costs including mechanical integrity test and other corrective actions costs; (4) site closure and post-closure care and monitoring. All costs items were separated into capital and operational expenditures.

The background information for the assessment of disposal costs per kW·h of electricity produced was provided by the country teams participating in this CRP. The information includes the amount of electricity generated during the lifetime of nuclear and fossil power plants, the amount of radioactive waste accumulated during the lifetime of the nuclear power plants and to be disposed of in the repository and the CO_2 disposal capacity. The units for the amount of accumulated radioactive waste were different for some countries, e.g. for India and

Cuba. In order to obtain cost estimates per t HM, a conversion coefficient was applied, i.e. the average amount of SNF generated per GW/year of net electricity produced by all reactors (39.9 t HM per GW·year) was applied to assess the amount of radioactive waste to be disposed of.

The information on costs presented by countries was not detailed enough to assess the net present value, and capital costs were given as overnight costs without accounting for interest during construction and without cost escalation. Therefore, the cost data were adjusted to a price level of 2010 and expressed in US dollars by applying prevailing exchange rates. All cost items were separated into capital and operational expenditures. The disposal costs per unit of electricity produced were assessed in capital and operational expenditures.

This chapter describes the main technical data on CO_2 and radioactive waste disposal, the main assumptions, costs and literature referenced for the CO_2 and radioactive waste cost estimates for specific countries (Cuba, Lithuania, Republic of Korea, Switzerland and India). The country cost data on CO_2 and radioactive waste disposal were obtained from national case studies and other documents, and are presented in local currency for some countries. The country cost data are expressed in $ and compared in Section 6.5.

Costs of CO_2 disposal were compared in detail for Lithuania and Cuba because other countries did not provide cost data. The costs of radioactive waste disposal were compared for four countries: India, Lithuania, Republic of Korea and Switzerland, because Cuba provided only the costs of low level radioactive waste disposal in a near surface repository and such cost data are incomparable.

The cost data presented in this chapter provide the original values from the country case studies and cited studies, but for the comparison tables, a common metric of $ 2010 is used by applying the appropriate GDP deflators and converting other currencies at average 2010 exchange rates.

6.3. COUNTRY CASE STUDIES

6.3.1. Cuba

6.3.1.1. Costs of CO2 disposal

Disposal concept

Many factors need to be considered in CO_2 disposal. Cost and performance estimates are critical factors in energy and policy analysis and, by necessity, employ many technical and economic assumptions that can dramatically affect the results. These parameters are: site characterization, monitoring, injection well construction, area of review and corrective actions, well operation, mechanical integrity test, post-injection well plugging, and site care, financial responsibility and general and administrative activities [6.19].

Unit costs are specified in terms of cost per site, per well, per square mile and other parameters depending on the characteristics of the cost item. The unit costs are applied to type cases which include specification for total area, depth, thickness, well injectivity, number of wells through time and other parameters [6.19]. Table 6.1 shows the main characteristics of the thermal power plant and the reservoir selected for CO_2 disposal.

TABLE 6.1. KEY PERFORMANCE PARAMETERS (BASE YEAR 2008)

No	Parameter	*Value or description*
(1)	Power plant type, fuel and capacity, MW	*Thermal power plant, fuel oil, 270*
(2)	Electricity produced per year, MWh	*1 229 904*
(3)	Utilization rate, % of the year	*0.52*
(4)	Life time of power plant, years	*15 after remodelling*
(5)	Average CO_2 emissions per year, million tons	*1.13*
(6)	CO_2 capture rate, %	*90 perspective*
(7)	CO_2 disposal type	*Depleted gas reservoir*
(8)	Location	*328896.58E, 2544203.93N Cuba. Onshore*
(9)	Number of wells	*1 injection well, 2 monitoring wells.*
(10)	Injection or Reservoir Depth, m	*1310*
(11)	Reservoir thickness, m	*33*
(12)	CO_2 supply pressure, MPa	*13,9 in the reservoir*
(13)	Reservoir horizontal permeability, mD	*3 (average)*
(14)	Stratigraphy	*Cretaceous (K2 cp-m^2)*
(15)	Lithology	*Gravel, marl, limestone etc.*
(16)	Number of wells in the area	*5*
(17)	Injection wells	*1*
(18)	Monitoring wells	*2*
(19)	Years of the project (injection of CO_2)	*15*
(20)	Volume of CO_2 to be disposed, Mt/year	*1.02*
(21)	*Disposal capacity, million m^3*	*74.4*

Total costs of CO_2 disposal

Cuba has not yet implemented geological disposal of CO_2 in any of its variants and no methodology has been developed to estimate its costs. On the basis of the methodology developed by the US EPA [6.19] for economic assessment of the geological disposal of CO_2, the data compilation of the oil activity in Cuba and a preliminary estimation of disposal cost of CO_2 (see Table 6.2) in the selected location were carried out.

TABLE 6.2. ESTIMATED COSTS USING THE EPA METHODOLOGY

No	Activities	Costs, Million $ (2010)
(1)	Geologic site characterization	0.3
(2)	Monitoring	2.7
(3)	Injection well construction	4.3
(4)	Area of review and corrective actions	0.2
(5)	Well operation	0.9
(6)	Mechanical integrity test	1.1
(7)	Post-injection well plugging, and site care	1.56
(8)	Financial responsibility	0.26
	Total cost	11.29

Considering the uncertainties referred to in the EPA methodology, the costs estimated could be higher considering the particular characteristics of Cuba.

6.3.1.2. Conclusions

Currently, geological disposal of CO_2 is not undertaken in Cuba. Official cost estimate of geological disposal of CO_2 has not been prepared. Cuba is considering CO_2 disposal into oil fields by applying the enhanced oil recovery (EOR) option. The estimated costs for this chapter were calculated by using the methodology of the EPA, which includes a prior estimate of an emission source and a disposal site.

The geological disposal of CO_2 are estimated to be around 0.732 $/t CO_2 or 0.06 US cent/kWh.

6.3.2. India

6.3.2.1. Costs of radioactive waste disposal

Disposal concept

The design of the Indian conceptual geological repository takes into consideration the disposal of 10 000 stainless steel overpacks containing vitrified high level waste at a depth of 400–500 m in granites. The proposed layout of the facility would spread over an area of about 2 × 2 km. A conceptual design and layout of a repository with a capacity of ten thousand overpacks has been developed for analysis with the application of suitable computer codes using site specific data on host rock properties, in situ geological conditions, overburden stresses, depth dimensions of underground excavations supplemented with radiological and thermal characteristics of overpacks. The conceptual design of the repository includes one main shaft (6 m) for accessibility and another ventilation shaft (4 m). The facility comprises two orthogonal transportation tunnels of 800 m length each. A total of 63 disposal tunnels (each of 110 m length), with the capacity to hold about 40 waste overpacks each, aligned at right angle to transportation tunnels have been included in the design. The disposal pit depth for hosting a 2 m long overpack has been fixed at 5 m with a diameter of 85 cm. A layer of compacted smectite clay bricks with a maximum thickness of 50 cm is proposed to be inserted between the overpack and the rock mass. The key performance parameters for radioactive waste disposal in India are presented in Table 6.3.

TABLE 6.3. KEY PERFFORMANCE PARAMETERS FOR RADIOACTIVE WASTE DISPOSAL IN INDIA.

No	Parameter	Value or description
(1)	Nuclear power plant type, fuel, total installed capacity, MW(e)	PHWR, UO_2 4780
(2)	Electricity produced during the life time, million MW·h	1592
(3)	Utilization rate, % of the year	Between 90–95
(4)	Life time of power plant, years	40
(5)	Radioactive waste disposal type	Multibarrier concept
(6)	Location, rock type	Granite
(7)	Underground depth of repository, m	500
(8)	The area of isolating rock zone, km^2	2 × 2
(9)	Containers used	SS canister in SS overpacks
(10)	Natural barriers	Granite,
(11)	Man-made barriers	Bentonite clay backfills and buffer
(12)	The amount of radioactive waste disposed, tHM (heavy metal)	7661 (estimated based on the average amount of SNF generated per GW/year for nuclear reactors (39.9 tHM)

Note: SS – stainless steel, SNF – spent nuclear fuel

Cost categories

Site characterization and selection activities

In India, site selection is based on the principle of screening large areas, measuring thousands of square kilometres in at least four to six regions in various parts of the country in stages and phases, based on well defined site selection criteria to systematically narrow down the area to a few promising zones of four to five square kilometres. The systematic site evaluation methodology has been developed and applied in larger regions occupied by granites through three distinct stages. In the initial stage, most of the information pertaining to geology, hydrogeology, structure and aspects related to socio-political and economic factors is derived from secondary datasets, mainly involving published reports of national agencies like the Geological Survey of India, Indian Meteorology Department, National Land Use and Soil Survey Department, Groundwater Survey Departments, National Geophysical Research Institute, etc. The information is integrated in a geographical information system (GIS) environment, preferably on a 1:250 000 scale. The second stage of investigation mainly focuses on the zones obtained through first stage investigations of large regions, and essentially involves data generation on 1:50 000 and 1:25 000 scales. The third stage of investigation is marked by very detailed geological and structural surveys on a 1:1000 scale, as well as geophysical surveys like resistivity, gravity, magnetic, etc. on a 50 × 50 m grid. The site has been further evaluated by means of 6000 m drilling and associated borehole based investigations. The cost estimates for various activities have been taken up based on data generated during the site characterization campaign and generic information from other mining projects in India. No specific cost estimation models currently available have been applied and the cost estimation have been made on very conservative parameters, mainly taking into considerations the expenditures involved in ongoing site characterization activities and URL development programmes (see Table 6.4).

TABLE 6.4. COST ESTIMATES FOR SITE SELECTION AND CHARACTERIZATION

No	Activity	Details	Cost, Million $ (2010)
(1)	Regional screening of promising area based on secondary data sets and satellite based imagery	Surveys on 1:50 000 scale,	5
(2)	Detailed geological, hydrogeological, structural surveys on various scales	On 1:50 000 to 1:1000 scale, pump tests	10
(3)	In situ stress and hydrogeological testing	Testing in at least 30–40 boreholes at regular interval	5
(4)	Geophysical surveys	Electrical, gravity and seismic surveys on 1:50 000 to 1:1000 scale for penetration up to 1km depth	10
(5)	Drilling operations	75–100 boreholes with total drilling of 20 000 to 30 000m	20
(6)	Laboratory based studies	5000 to 7000 samples of rock water, soil and other media	10
(7)	Generic URL site characterization and construction and experiments	Shaft sinking, excavation of drives and major experiments	30

Note: The cost data includes only site selection, construction of the facility and R&D projects and excludes waste immobilization, interim storage and transport.

Construction

The total costs of construction are 500 million $ (Table 6.5).

TABLE 6.5. COST ESTIMATION FOR CONSTRUCTION

No	Activity	Details	Cost Million $ (2010)
(1)	Main and ventilation shaft sinking and associated mechanical systems	One access shaft 500 m deep with 6 m diameter, one auxiliary shaft for ventilation	50
(2)	Excavation of two transportation tunnel (800m each), 63 disposal tunnels		100
(3)	Excavation of 10 000 disposal pits, waste emplacement and erection of engineered barriers	5 m deep, spaced at 2.5 m	100
(4)	In situ measurements and other underground characterization studies	Stress and hydraulic conductivity measurements	25
(5)	Sealing and grouting of fracture and other support systems	As per requirements	25
(6)	In situ URL base experiments	Mainly TMH experiment, FTT	50
(7)	Electrical systems	60 years of operations	50
(8)	Ventilation systems and transportation system	As per requirements	100
	Total		500

Note: TMH – Thermal-Mechanical-Hydraulic, FTT – Fracture Toughness Test

Operation

The operation cost in the Indian case will mainly include transportation of waste overpacks from vitrification and interim disposal facilities to the disposal site, their surface storage at the repository site, and transport of overpacks to underground location of disposal, their emplacement into disposal pits, erection of engineered barriers and closure of disposal pits. The operation period has been estimated to be in the order of 60 years. Other operational activities adding to the costs include radiological monitoring, decontamination of handling equipment, repair and replacement of waste handling and emplacement systems, etc. A preliminary estimate during the operational phase of geological repository is of the order of 300 million $.

No detailed estimation of costs related to closure and post-closure activities has been made in India, but a preliminary assessment based on generic datasets indicates a total cost of 100 million \$. Total costs of radioactive waste disposal in India are obtained by summing up costs of site exploration and improvement, engineering, radioactive waste handling, disposal operation and maintenance, site closure and administrative costs (Table 6.6).

TABLE 6.6. COST COMPONENTS FOR RADIOACTIVE WASTE DISPOSAL IN INDIA

No	Cost component	Capital costs, Million \$ (2010)	Operational expenditures, Million \$ (2010)	Total, Million US \$ (2010)
(1)	Site exploration and improvement costs (repository development, site investigation etc.) including URL cost	100		100
(2)	Engineering costs (underground and above ground facilities, excavation, repository construction, monitoring, etc.)	500		500
(3)	Waste handling, disposal operation and maintenance costs (expenses for labour, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)		300	300
(4)	Site closure and post-closure costs (site care, monitoring, etc.)	100		100
(5)	Administrative costs	50		50
	Total	750	300	1050

Using information from Table 6.6 on electricity generation by all power plants during their operation time (1592 million MW·h) and their assessed amount of accumulated radioactive waste (7661 tHM), the costs of radioactive waste disposal per t HM and kW·h of electricity generated can be evaluated. Radioactive waste disposal costs in India amount to 137 058 t HM and 0.7 \$/MW·h or 0.07 US cents/kW·h, and are quite low compared with radioactive waste disposal costs found in the literature review presented in Section 6.1.

6.3.2.2. Conclusions

The studies related to CO_2 disposal in India are currently focused on estimation of the CO_2 disposal potential in various geological formations. There are no estimates for cost of CO_2 geological disposal. Therefore, the costs of CO_2 disposal are not included in this section and comparative analysis of back end technologies for India has not been performed.

The radioactive waste disposal cost estimates for India are made for site selection, characterization, construction, operation and closure. These estimates are based on a conceptual design of deep geological disposal facility and do not include the costs of waste treatment, immobilization, transportation, interim disposal and monitoring. Radioactive waste disposal costs in India amount to 0.07 US cents/kW·h for a total of 137 058 t HM and are quite low compared to those in other countries.

6.3.3. Republic of Korea

6.3.3.1. Costs of radioactive waste disposal

Disposal concept

High level radioactive waste disposal costs largely relate to above ground facilities and the underground facilities of a repository. According to a cost analysis undertaken in Finland, costs required for building above ground facilities are approximately twice the construction costs of underground facilities [6.35]. An underground facility is required to dispose of the spent fuel generated from a power plant in a place deep underground in order to safely isolate it from the biosphere for a long period of time. As no spent fuel repository has been built in the Republic of Korea to date, it is difficult to accurately estimate the costs of repository construction. For this reason, data from a reference repository is used in this study [6.36]. The main parameters of the radioactive waste disposal facility in the Republic of Korea are presented in Table 6.7.

Cost categories

Cost items for a disposal cost estimate are divided into three categories such as investment costs, operational costs and closure costs. It is essential to estimate the most dominant cost driver for high level radioactive waste disposal. According to the former studies, it was found that the most critical cost driver for surface facilities for an HLW repository were the manufacturing costs of the canisters [6.37] because of their outer shell is made of very expensive copper. Thus, the Korea Atomic Energy Research Institute (KAERI) has changed the dimensions of its canister to increase the loading capacity of the spent fuel, and also the manufacturing method of the outer canister from a thick-plate fabrication method to a cold spray coating method [6.36].

To dispose of more spent fuel in a deep rock, KAERI developed a parallel operating system for a repository through collaboration with POSIVA in Finland. Both the excavations and the operation to install a canister into a disposal hole will be performed simultaneously for 25 years [6.38]. Thus, this parallel work can be considered for 25 years to calculate the costs with respect to the conceptual design of a repository. In addition, a longer operational duration may be needed to dispose of more spent fuels continuously from a nuclear power plant, or to achieve retrievability of an HLW repository at a depth of 500 m below the ground level in a stable plutonic rock body. In this sense, an extended operational duration for an HLW repository affects the overall disposal costs [6.39].

KAERI has collaborated with Atomic Energy of Canada Limited (AECL) to estimate the costs of surface facilities for an HLW repository since 2007. From these results, the canister costs turned out to be the most dominant cost factor for surface facilities, and the personnel costs were also significant in the operational costs [6.40]. In the Republic of Korea, the unit manufacturing cost of the canister was estimated to be 163 586 EUR [6.37]. It was estimated that 2835 canisters would be required to dispose of 16 000 tU of CANDU spent fuel in a deep rock. Thus the canister costs will be one of the dominant cost drivers.

TABLE 6.7. KEY PERFORMANCE PARAMETERS FOR RADIOACTIVE WASTE DISPOSAL IN THE REPUBLIC OF KOREA

No	Parameter	Value or description
(1)	Nuclear power plant type and capacity, MW	24 PWRs (about 1000 MW(e)/PWR), 4 PHWRs (about 700 MW(e)/PHWR)
(2)	Electricity produced during the life time of nuclear power plant, million MW·h	8545
(3)	Average annual utilization rate of NPP, %	About 91
(4)	Life time of power plant, years	40 years
(5)	Radioactive waste disposal type	KBS-3 vertical Type
(6)	Location, rock type	Not determined but preferably granite
(7)	Underground depth of Repository, m	About 500 m
(8)	The area of isolating rock zone, km^2	About 4.6 km^2
(9)	Type and amount of containers used	Inner vessel: modular cast iron, outer shell: copper
(10)	Natural barriers	Host rock : granite
(11)	Man-made barriers	Engineered barrier: disposal canister, buffer, backfill
(12)	The amount of radioactive waste for disposal, tHM (Heavy metal)	36 000 (PWR: 20 000 tHM; CANDU: 16 000) tHM)

Note: PWR – pressurized water reactor, PHWR – pressurized heavy water reactor, CANDU – Canada deuterium uranium

In the Korean Reference Disposal System (KRS), the duration of disposing the PWR and CANDU spent fuel into disposal holes is called the operational duration. The feasibility study of operating a repository for 55 years should be performed to assess its economic performance.

The main items of the operational costs are composed of the backfilling costs of the tunnels, bentonite costs of the disposal holes, and the personnel costs. Among these costs, it was estimated that a significant charge for the operational costs were the personnel costs. But the excavation costs to a depth of 500 m are not well known. The estimated personnel costs will be 1 556 000 EUR or 2 041 000 $ per year, so the total costs for 80 years are estimated to be 124 480 000 EUR or 163 321 000 $. The main cost components for radioactive waste disposal in the Republic of Korea are presented in Table 6.8.

TABLE 6.8. COST COMPONENTS OF RADIOACTIVE WASTE DISPOSAL IN THE REPUBLIC OF KOREA

No	Cost component	Capital expenditure, Million $ (2010)	Operational expenditure, Million $ (2010)	Total, Million $ (2010)
(1)	Project administration, R&D, site exploration and improvement costs (repository development, site investigation, etc.)	1481		1481
(2)	Engineering costs (underground and above ground facilities, infrastructure construction, excavation, repository construction, monitoring, etc.)	6641		6641
(3)	Waste handling and disposal operation and maintenance costs (expenses for labour, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)		11 176	11 176
(4)	Site closure and post-closure costs (site care, monitoring, etc.)	273		273
	Total	8395	11 176	19 571

Using information from Table 6.7 on electricity generation by all power plants during their operation time (8545 million MW·h) and assessed amount of radioactive waste accumulated (36 000 t HM), the costs of radioactive waste disposal per t HM and kW·h of electricity generated can be calculated. Radioactive waste disposal costs in the Republic of Korea amount to $ 543 639 t HM and 0.23 US cents/kW·h and are very high compared with radioactive waste disposal costs presented in Section 6.1.

6.3.3.2. Conclusions

No specific CO_2 geological disposal site has been identified in the Republic of Korea. No information on cost estimation is available for CO_2 pre-processing, the establishment or the operation of disposal facilities due to the absence of a CO_2 disposal reference system. Therefore, the costs for a comparative analysis of back end technologies have not been performed.

As no spent fuel repository has been built in the Republic of Korea to date, it is difficult to accurately predict the costs of the repository construction. For this reason, data from a reference repository is used in this study. The Swedish concept KBS-3 vertical was applied by KAERI for the development of the repository. Radioactive waste disposal costs for a quantity of 543 639 t HM amount to 0.23 US Cents/kW·h, which are very high compared to radioactive waste disposal costs analysed in Section 6.1.

6.3.4. Lithuania

6.3.4.1. Costs of radioactive waste disposal

Disposal concept

Some 22 000 nuclear fuel assemblies, an equivalent of approximately 2500 tonnes of uranium, were used at the Ignalina NPP throughout its operation. All these assemblies should be stored for about 50 years and then be disposed of. In order to manage and dispose of the SNF, the long lived radioactive waste will be transported from the Ignalina NPP to the deep geological repository, that is assumed to be operational in 2041 [6.41], [6.42]. The disposal concept for RBMK-1500 SNF in crystalline rocks is based on the Swedish KBS-3 concept [6.27], with radioactive waste emplacement into copper canisters with cast iron insert. The bentonite and its mixture with crushed rock are foreseen as buffer and backfill material. About 1400 canisters will be required [6.43], [6.44]. The main parameters of radioactive waste disposal in Lithuania are presented in Table 6.9.

Cost categories

The general stages for SNF disposal are: pre-operation, operation and post-operation phases [6.1]. A cost estimation for the model case of deep repository in Lithuania has been carried out. This preliminary cost assessment is based on experience accumulated during the development of the Swedish KBS-3V concept [6.27] and is now applied to the Lithuanian case. In order to give some guarantees to cover the loss as a result of future unforeseen events, reasonable additional costs (cost variations) are included in the calculations. The same methodology as in Sweden for the cost assessment of SNF disposal has been employed [6.45]. The result gives a mean value of the cost (future costs) and the standard deviation of the cost for the chosen 50% degree of confidence [6.46].

Planning, preliminary research and administration

The Lithuanian Radioactive Waste Management Agency (RATA) is engaged in permanent administration activities related to the disposal of SNF and long lived waste. It is foreseen that approximately 20 persons from RATA's staff and about 150 people from outside of RATA will be involved in waste handling and research works. The costs of planning, administration and preliminary research were evaluated to be in the range 200–224 million Lithuanian litas (Lt) (2005) or 76–85 million $.

The main purpose of the research, development and demonstration (RD&D) programme is to collect the necessary information, knowledge and data to realize final disposal of SNF and other long lived radioactive wastes. The costs of the RD&D programme and safety analysis are evaluated in the range of 859–1064 million Lt (325–404 million $) (2005) [6.46].

Site characterization and selection activities

The basic objective of the site characterization process is to select a suitable site for the disposal of SNF and long lived waste and to demonstrate that the selected site, in conjunction with a deep repository design and radioactive waste package, has properties which provide adequate isolation of radionuclides from the biosphere for the desired period of time. The cost estimate for site characterization is based on the Swedish methodology [6.27] and amounts to 334–421 million Lt or 127–160 million $ (2005) [6.46].

TABLE 6.9. KEY PERFORMANCE PARAMETERS FOR RADIOACTIE WASTE IN LITHUANIA.

No	Parameter	Value or description
(1)	Nuclear power plant type, capacity, MW and fuel	2 RBMK-1500 MW(e) reactors, uranium
(2)	Electricity produced during the life time of nuclear power plant, million MW·h	307.9
(3)	Average utilization rate, % of the year	80
(4)	Life time of power plant, years	21
(5)	Radioactive waste disposal type	Swedish concept (KBS-3V)
(6)	Location, rock type	Crystalline rock
(7)	Underground depth of repository, m	300–500
(8)	The area of isolating rock zone, km^2	0.4
(9)	Type and amount of containers used	2400 copper canisters with cast iron insert
(10)	Natural barrier	Granite
(11)	Man-made barrier	Bentonite
(12)	Amount of radioactive waste for disposal, t HM	7945

Construction

The construction of the system (rail) needed to transport radioactive waste from the interim storage site (Ignalina NPP) to the encapsulation plant (deep repository site) is considered. It is intended to use the same transport system for the immobilized long lived waste from the interim storage to the deep repository. It is assumed that the deep repository will be about 120 – 200 km from the Ignalina NPP, but not more than 350 km (largest distance across Lithuania). Investments in the transportation system are estimated to be in the order of 239–309 million Lt or 91–117 million $ [6.46].

Before the radioactive waste is emplaced in a deep repository, it must be encapsulated in canisters. One canister contains 32 RBMK fuel half-assemblies. It is estimated that approximately 1400 copper canisters of the Swedish type will be necessary for the disposal of all spent fuel from the Ignalina NPP. It is assumed that the capacity of the plant will be 50 canisters per year. Encapsulation is planned to take place in the area of the deep repository.

The plant will be dismantled and decommissioned at the end of the deposition period. The construction costs of the encapsulation plant are estimated in the range of 851–1188 million Lt or 323–451 million $. The costs of decommissioning are included in the investments costs. The investments into facilities above ground (operation sites) for the deep repository are about 701–947 million Lt or 266–360 million $ (2005). The investments into underground facilities (shafts, access tunnels and service areas) are about 945–1366 million Lt or 359–519 million $ (2005). The investments into other underground facilities such as deposition panels are about 105–146 million Lt or 40–55.5 million $ (2005). The investments into a deep repository are about 43–51 million Lt or 16.3–19.4 million $ (2005). All these investment costs include costs of closure and decommissioning costs, as well. The investment costs of the interim storage of spent fuel are not included in these cost estimates [6.46].

Operation

The costs of operation, maintenance and decommissioning of an interim storage (including costs of the disposal containers and waste conditioning) have been estimated as part of the deep repository costs. The operation and maintenance of the transportation system are estimated to be 73–90 million Lt or 27.7–34.2 million $ (2005). Operation and maintenance costs for the encapsulation plant are assessed in the range of 317–410 million Lt or 120.4–155.8 million $ (2005). The operation and maintenance costs for canisters amount to 295–402 million Lt or 112.1–152.7 million $ (2005). The operation and maintenance costs of the above ground facility are about 565–722 million Lt or 214.6–274.3 million $ (2005). The operation and maintenance costs of the underground facilities (shafts, access tunnels and service area) are 48–50 million Lt (2005). The costs of backfill are approximately 129–171 million Lt or 49–65 million $ (2005). O&M costs for deposition panels are 38–50 million Lt or 14.4–19 million $ (2005). The O&M costs for deep repository including backfill costs are estimated to be 343–401 million Lt or 130.3–152.4 million $ (2005) [6.46].

The costs of closure, verification and monitoring are included in the investment costs of above ground and underground facilities and deep repository of radioactive waste. The total costs of radioactive waste disposal are summarized in Table 6.10. The costs assessed in Litas (2005) were converted into $ (2010) by taking into account the exchange rates and annual inflation rates over the period 2005–2010.

Table 6.10 shows the estimated future costs with a 50% probability for the radioactive waste management system according to the reference scenario. The costs for different facilities are reported here in the following items (cost categories): investment, operation and maintenance, decommissioning and backfill. Investment costs normally only include those costs that arise before a facility is put into operation. The difference of approximately 32% (~ 2200 million Lt or about 840 million $) of the future costs in comparison to reference costs gives guarantees of 50% to cover the loss due to unforeseen future events and uncertainties (cost variations) estimated in the calculations.

TABLE 6.10. COST COMPONENTS OF RADIOACTIVE WASTE DISPOSAL IN LITHUANIA

No	Cost component	Capital expenditure, million Lt (2005)	Operational expenditure, million Lt (2005)	Total, million Lt (2005)	Total, million $ (2010)
(1)	Programme administration, R&D, site exploration and improvement costs (repository development, site investigation, etc.)	1393–1709		1393–1709	500–600
(2)	Engineering costs (underground and above ground facilities, infrastructure construction, excavation, repository construction, monitoring, etc.)	2893–4007		2893–4007	1000–1400
(3)	Radioactive waste handling and disposal operation and maintenance costs (expenses for labour, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)		2244–2875	2244–2875	800–1000
(4)	Site closure and post-closure costs (site care, monitoring, etc.)	-	-	-	-
	Total	4286–5716	2244–2875	6530–8591	2300–3000

6.3.4.2. Costs of CO_2 disposal

Disposal concept

Only two large aquifers in the Baltic States meet the requirements for CO_2 disposal: the Lower-Middle Devonian (Pärnu-Kemeri formations) and Middle Cambrian aquifers, located at depths exceeding 800 m in the central and western parts of the Baltic basin [6.47]. The thickness of the aquifers is in the range of 20–70 m [6.48]. There are three potential geological aquifer structures in south-west Lithuania: Vaskai (8.7 million t), Syderiai (21.5 million t) and D11 (11.3 million t), which can store a total of 41.5 Mt of CO_2 [6.47]. Syderiai has the highest potential therefore this option was selected for the assessment of CO_2 disposal costs in Lithuania. The main characteristics of the Syderiai geological structure for the CO_2 disposal are presented in Table 6.11. CO_2 emissions from the main power plants are about 2.1 Mt/year. The electricity produced per year corresponds to the operation of thermal power plant with a capacity of 1800 MW.

TABLE 6.11. MAIN CHARACTERISTICS OF CO_2 DISPOSAL IN THE SYDERIAI GEOLOGICAL STRUCTURE IN LITHUANIA

No	Parameter	Value or description
(1)	Power plant type, fuel and capacity, MW	Thermal power plant, natural gas and HFO, 1800 MW
(2)	Average annual electricity generation MW·h	2 938 000
(3)	Power plant utilization rate, % of the year	65
(4)	Average CO_2 emissions per year, million t	2.4
(5)	CO_2 capture rate, %	90
(6)	CO_2 disposal concept	Saline aquifer
(7)	Seismicity	3-D
(8)	CO_2 disposal capacity at 100% disposal efficiency, million m^3	100
(9)	Stratigraphy	Middle Cambrian
(10)	Lithology	Sandstone
(11)	Area of well spacing, km^2	26
(13)	Number of injection wells	3
(14)	Total number of monitoring wells	1
(15)	Injection pipe diameter, m	0.14
(16)	Injection depth, m	1458
(17)	Reservoir thickness, m	57
(18)	CO_2 supply pressure, MPa	15.3
(19)	Reservoir horizontal permeability, mD	400
(20)	Disposal efficiency factor	0.3
(21)	CO_2 disposal capacity, Mt	21.5
(22)	Injection period (years)	10
(23)	Volume of CO_2 disposed	21.5 Mt

There are no cost estimates available for CO_2 disposal in Lithuania. The methodology developed by the US EPA [6.19] was applied for assessing CO_2 disposal costs in the Syderiai geological structure in this study.

The main cost components for CO_2 disposal applied in EPA studies (2010) are the following: site characterization, injection well construction, monitoring, well operation, mechanical integrity test, area of review and corrective actions, site closure (post-injection well plugging and site care), financial responsibility and administrative costs. The same cost components were applied for CO_2 disposal assessment at Syderiai.

The costs of site characterization are highly dependent on the requirements of the regulatory regime for the project. However, given that CO_2 should be isolated from the atmosphere for long timescales, it would be prudent to monitor the surface of the area in which the injected CO_2 is likely to spread over a set time horizon, to ensure that conduits to the surface, natural or otherwise, do not exist. Therefore, the main factor affecting the costs of site characterization will be the overall size of the area under consideration. McCoy suggests the approximate costs associated with characterising this area to be about \$38 610 per km^2 for geophysical characterization (3-D seismic); \$ 3 000 000 to drill and log a well; and an additional 30% of these total costs for data processing, modelling and other services [6.17]. One well would be required for every 65 km^2 of the review area [6.17]. These costs for the Syderiai disposal would be about 1 million \$ for geophysical investigation, 30 million \$ for drilling the well and 9 million \$ additional costs related to data processing and modelling. The total costs of site characterization are about 3.2 million \$ (2008). The site characterization costs for the pilot project in saline aquifers for different regulatory regimes in the USA are evaluated to be in the range of 1.4–4.4 million \$ (2008) [6.20]. Table 2 of reference [6.17] presents unit costs for site characterization (per site and per square mile surveyed) developed for the USA; the site characterization costs for the Syderiai disposal (surveyed area of about 42 km^2) amounts to 1.9 million \$ (2008).

The design of the monitoring wells is included in the monitoring section. Injection well construction costs include the development of standard plans associated with current Underground Injection Control regulations (e.g. the drilling and casing plan, wellhead equipment plan, and downhole equipment selection), as well as pre-operational logging, sampling and testing. Costs are specified as a base cost per site and a cost per injection well in Table 4 in reference [6.19]. The injection well construction costs for the pilot project in saline aquifers for different regulatory regimes in the USA are evaluated to be in the range of 9.1–9.7 million \$ (2008) [6.20]. The costs of injection well construction for the Syderiai geological structure are evaluated at 9 million \$ (2008) based on unit costs presented in Table 4 in reference [6.19].

Once the injection begins, a program for monitoring conditions in the injection zone and CO_2 distribution is required. This is needed in order to: manage the injection process; delineate and identify leakage risk or actual leakage; verify and provide input into computational models; and provide early warnings in case of failures. The monitoring costs for the pilot project in saline aquifers for different regulatory regimes in the USA are estimated in the range of 0.52–1.26 million \$ (2008) [6.20]. Table 3 in reference [6.19] presents unit costs for monitoring. Monitoring costs for the Syderiai geological structure are about 1 million \$ (2008).

The operation costs comprise cost elements related to the operation of the injection wells, including measuring and monitoring equipment, electricity costs, O&M costs, space costs, repair and replacement of wells and equipment, and estimated costs for the possibility of failure at the site and the need to relocate a geological disposal operation. The operation costs for the pilot project in saline aquifers for different regulatory regimes in the USA are estimated in the range of 1.2–2.1 million $ (2008) [6.20]. Based on Table 6 in reference [6.19], the operation costs for the Syderiai geological structure are about 1 million $.

Owners or operators of CO_2 injection wells must periodically evaluate the well integrity to ensure mechanical soundness, status of corrosion and ability to sustain pressure. These technologies are well established and have been used for decades for underground injection operations. The costs of the mechanical integrity test of the pilot project in saline aquifers for different regulatory regimes in the USA are estimated in the range of 13 215–13 500 $ (2008) [6.20]. Based on Table 7 in reference [6.19], the costs of the mechanical integrity test for the Syderiai geological structure are about 13 000 $ (2008).

The next component of the cost analysis includes fluid flow and reservoir modelling to predict the movement of the injected CO_2 and pressure changes during and after injection. It also includes those cost elements pertaining to the identification, evaluation and remediation of existing wells within the area of review. The corrective actions for the pilot project in saline aquifers for different regulatory regimes in the USA are in the range of 0.53–1.1 million $ (2008) [6.20]. Based on Table 5 in reference [6.19], the costs of corrective actions for the Syderiai geological structure are about 560 000 $.

After the injection phase has ended, the owner or operator must close the site in a safe and secure manner and monitor the site during the post-injection period before final handover to a state or national authority. The site closure costs for a pilot project in saline aquifers for different regulatory regimes in USA are evaluated to be in the range 0.17–0.9 million $ (2008) [6.20]. Based on Table 9 in reference [6.19], the costs of site closure for the Syderiai geological structure are about 180 000 $ (2008).

The total costs of CO_2 disposal are summarized in Table 6.12. The costs assessed in $ (2008) were converted into $ (2010) by taking into account the exchange rate and annual inflation rate of 1.4% for the period 2008–2010.

TABLE 6.12. COST COMPONENTS FOR CO_2 DISPOSAL IN LITHUANIA

No	Cost component	Total, Million $ (2008)	Total, Million $ (2010)
(1)	Programme administration, R&D and site characterization costs	1.9	1.95
(2)	Engineering costs (injection well construction, etc.)	9	9.25
(3)	Monitoring costs	1	1.03
(4)	Well operation costs including mechanical integrity test, area review and corrective actions costs	1.6	1.65
(5)	Site closure and post-closure costs (site care, monitoring, etc.)	0.2	0.21
	Total	13.7	14.1

6.3.4.3. Comparative assessment of radioactive waste and CO_2 disposal costs

The comparative assessment of radioactive waste and CO_2 disposal in Lithuania is presented in Table 6.13. The radioactive waste disposal costs in Lithuania amount for a total of 377 596 t HM to 0.97 US Cents/kW·h, which is quite low in comparison with radioactive waste disposal costs analysed in the introduction of this chapter. CO_2 disposal costs in Lithuania are 0.7 \$/t CO_2 and 0.05 US cent/kWh, radioactive waste disposal costs per kW·h in Lithuania are significantly higher than CO_2 disposal costs.

TABLE 6.13. COMPARATIVE ASSESSMENT OF RADIOACTIVE WASTE AND CO_2 DISPOSAL IN LITHUANIA

Disposal option	Radioactive waste disposal	CO_2 disposal
Implementation	Planned	Research
Evaluation method	Based on study conducted	Based on own assessment
Disposal concept	KBS-3V	Saline aquifer
Depth, m	300–500	1458
Life time (years)	100	15
Total cost, million USD (2010)	3000	14.1
Disposal capacity	7945 t HM	21.5 million m^3
Electricity generated during life time, million MW·h	307.9	29.4
Disposal costs/kW·h, US cents/kW·h (2010)	0.97	0.05
Disposal costs/t HM or CO_2, US \$ (2010)	377 596	0.7

6.3.4.4. Conclusions

There are no plans in Lithuania to develop CO_2 disposal projects. So far, only preliminary estimates of the CO_2 disposal potential have been evaluated; there are no specific cost calculations. For this study, the Syderiai geological structure, which has the highest potential for CO_2 disposal, was selected for costs assessment. The disposal costs were assessed by applying the cost model and the unit costs developed by the US EPA because of the lack of information in Lithuania [6.20]. Total costs of CO_2 disposal in Lithuania in the Syderiai geological structure are about 14.1 million \$ (2010), that is 0.7 \$/t CO_2 and 0.05 US cent/kW·h.

Lithuania closed the Ignalina NPP in 2009 and is considering radioactive waste disposal. The costs were assessed based on studies conducted in the country. The total costs of radioactive waste disposal are about 3000 million \$, that is about 377 596/t HM and 0.97 US cents/kW·h.

The comparative cost analysis of radioactive waste and CO_2 disposal in Lithuania indicates that radioactive waste disposal costs are significantly higher than CO_2 disposal costs per unit of electricity produced.

6.3.5. Switzerland

6.3.5.1. Costs of radioactive waste disposal

Disposal concept

The proposed final disposal facility for SF, HLW, intermediate and LLW consists of a series of horizontal emplacement tunnels located at a depth of approximately 650 m in the centre of an Opalinus Clay formation running from the west to the north-east of Switzerland. The repository proposed for LLW would be excavated in the same geological formation but at a depth between 300 and 400 m [6.49].

The SF assemblies of either PWR or BWR reactor types are located inside 150 mm thick cast steel canisters with a minimum design lifetime of 1000 to 10 000 years. Recovery of useable fissile products can be achieved. The vitrified HLW resulting as a byproduct of SF reprocessing is enclosed within stainless steel flasks which are also enclosed within cast steel outer canisters. ILW may require different primary containment, depending on the radionuclides included in the waste. Generally, both ILW and LLW are processed in a similar way by being immobilized in a solidifying substance (cement or bitumen) inside steel drums and cumulatively disposed inside concrete boxes. ILW will, however, be placed in the repository at a lower volume concentration of waste containers, and due to its longer lived activity than LLW, repository concepts specify ILW as a separate aspect of the HLW and SF final repository [6.49], [6.50].

In Table 6.14, the quantities of spent fuel are given, assuming a lifetime of the power plants of 60 years. Sufficient capacity for interim storage in various facilities in Switzerland is available for all these wastes.

TABLE 6.14. SWISS NUCLEAR POWER PLANTS, CAPACITIES, SPENT FUEL QUANTITIES AND REPOSITORY CONCEPT [6.49]

No	Parameter	Value or description
(1)	Nuclear power plant type, fuel and capacity, MW(e)	PWR, UO_2 & MOX, 1715 MW(e) BWR, UO_2, 1537 MW(e)
(2)	Electricity produced during the life time of power plant, million MW·h	1536
(3)	Utilization rate, % of the year	90%
(4)	Life time of power plant, years	60
(5)	Radioactive waste disposal type	Horizontal emplacement tunnels
(6)	Location, rock type	Opalinus clay
(7)	Underground depth of repository, m	650
(8)	The area of isolating rock zone, km^2	1.5
(9)	Containers used	Cast steel canisters
(10)	Natural barriers	Opalinus clay
(11)	Man-made barriers	Containers, backfill, concrete repository lining
(12)	Amount of radioactive waste for disposal (t HM)	3217

Note: PWR – pressurized water reactor, MOX – mixed oxide, BWR – boiling water reactor

Financing radioactive waste management

In Switzerland, the producers of radioactive waste are obliged by law to dispose of the waste safely and at their own cost. The waste management costs which arise during the operation of the NPP (e.g. for reprocessing of spent fuel, investigations by the Nagra, construction of interim storage facilities) are covered on an ongoing basis. The decommissioning costs and the costs of radioactive waste management arising after the nuclear power plants cease operation are secured by payments made by the owners into two independent funds: the decommissioning fund and the waste management fund [6.51].

- The decommissioning fund for nuclear installations was set up on 1st January 1984 to cover the costs of decommissioning and dismantling closed nuclear facilities and to dispose of the waste arising from these activities. According to the most recent cost estimates, the decommissioning costs for the five nuclear reactors and for the interim disposal facilities will amount to around 2.2 billion CHF (price basis 2006) or 2.4 billion \$. At the end of 2007, the accumulated capital in the decommissioning fund was 1322 billion CHF or 1.44 billion \$ (2006: 1.324 billion CHF or 1.44 billion \$, 2005: 1.252 billion CHF or 1.36 billion \$);

- The waste management fund for NPPs was set up on 1st April 2000 in order to cover the costs of managing operational waste and spent fuel after the NPPs have ceased operation. All NPP operators are obliged to make contributions to the fund, with the first contributions made in 2001. Waste management comprises all the activities leading up to the emplacement of the waste in a deep geological repository, as well as the emplacement of wastes and the activities associated with a monitoring phase and closure of the repository. According to the most recent cost estimates, the waste management costs will amount to around 13.4 billion CHF or 14.6 billion \$, based on 2006 prices. The fund will be required to accumulate around 6.3 billion CHF or 6.9 billion \$ (due to interest rates and further payments). At the end of 2006, the accumulated capital in the waste management fund was 3.013 billion CHF or 3.278 billion \$;
- In 2008, the utilities submitted general license applications for three new NPPs (Generation III), two of them were planned to replace the oldest Swiss facilities (Beznau 1 & 2 and Mühleberg) and expiring electricity import contracts, which therefore required the consideration of a larger waste inventory. However, following the Fukushima NPP accident, the Swiss government is now largely against the planning of any new NPPs [6.52]. The figures given in Table 6.15 represent the volumes and costs for existing NPPs only.

Total radioactive waste disposal costs in Switzerland are estimated to be 7762.9 million \$ or 2 413 087 \$/ t HM and 0.51 US cents/kW·h.

6.3.5.2. Costs of carbon dioxide disposal

The options for CO_2 disposal are being assessed within the ongoing CARMA research project [6.53]. With only a very small fraction of electricity produced in Switzerland from fossil fuel power plants (<5%), it is not necessary to look for carbon reduction measures such as CO_2 disposal in the electricity generation sector today. The largest point source emitters of CO_2 in Switzerland are industrial facilities, particularly cement production where the current annual emissions of CO_2 are approximately 11.3 Mt [6.54].

The project Carbon Management in Power Generation (CARMA) [7.53] prepared the first appraisal of the potential for deep geological sequestration of CO_2 in Switzerland [6.55], also reported in the study by the Federal Agency for Energy (Bundesamt fuer Energie) [6.56]. Following a numerical scoring and weighting scheme on a scale 0–1, they determined that the combined volumes of the four main candidate aquifers with potentials above 0.6 offer a theoretical, effective disposal capacity of 2680 Mt of CO_2. Future fossil fuelled power stations in Switzerland would most probably be natural gas combined cycle plants because of the lack of indigenous fossil resources, the existence of natural gas pipelines and the lower CO_2 emissions per kW·h of natural gas compared with coal. A 400 MW(e) combined cycle gas power station produces approximately 0.7 Mt CO_2/year (assuming 360 kg/MW·h and 5000 hours/year operation).

TABLE 6.15. DISPOSAL COSTS FOR RADIOACTIVE WASTE GENERATED DURING THE LIFETIME OF EXISTING NPPs IN SWITZERLAND (MILLION SWISS FRANCS IN 2006) [6.51]

No	Cost component	Capital expenditure	Operational expenditure	Total
(1)	Site exploration and improvement costs (repository development, site investigation, etc.)	1139 (L&ILW) 1724 (SF&HLW)		1139 (L&ILW) 1724 (SF&HLW)
(2)	Engineering costs (underground and above ground facilities, excavation, repository construction, monitoring, etc.)	447 (L&ILW) 495 (SF&HLW)		447 (L&ILW) 495 (SF&HLW)
(3)	Waste handling and disposal operation and maintenance costs (expenses for labour, chemicals, surface and underground equipment maintenance, cost of energy to operate equipment, etc.)		360 (L&ILW) 610 (SF&HLW)	360 (L&ILW) 610 (SF&HLW)
(4)	Site closure and post-closure costs (site care, monitoring, etc.)	189 (L&ILW) 449 (SF&HLW)		189 (L&ILW) 449 (SF&HLW)
	Total	1774 (L&ILW) 2668 (SF&HLW)	360 (L&ILW) 610 (SF&HLW)	2134 (L&ILW) 3278 (SF&HLW)
	Total, million USD (2010)	6371.6	1391.4	7762.9

The research concluded that the existing disposal capacity for CO_2 from electricity generation and other industrial activities are more than sufficient to serve the needs for many decades. This is, however, only a preliminary study based on literature, and the actual disposal potential estimated from physical and geological examination of the area may prove to be very different. Being at such an early stage in the feasibility assessment, potential costs of CO_2 disposal in Switzerland have not yet been estimated.

6.3.5.3. Conclusions

Due to the very early stage of the evaluation of CO_2 disposal potential, it was only possible to present economic details of radioactive waste disposal for Switzerland. In this area, design proposals have been drafted and the specific costs have been determined. In terms of the overall process of radioactive waste management, certain steps are implemented simultaneously with normal operation of the power plants, and for this the NPP operators have been paying on an ongoing basis. For the costs of radioactive waste management after the operational lifetime of the NPPs and for the construction of geological repositories, NPP operators have been legally obliged to contribute to established funds since April 2000, and for the decommissioning of NPPs since 1984. Of the 13.4 billion Swiss francs overall required to meet the SF and radioactive waste management costs, the fund will need approximately 6.3 billion Swiss francs. In 2006, the balance stood at a little over 3 billion. Assuming the continued operation of all currently existing NPPs, the required funds should be accumulated well before the NPPs are decommissioned.

6.4. COMPARATIVE ASSESSMENT

The comparison of radioactive waste disposal costs between Lithuania, Switzerland, India and the Republic of Korea is presented in Table 6.16. The conversion rates used to convert local currencies to $ (2010) are presented in Table 6.17.

As one can see from Table 6.16, the highest costs per t HM were obtained for Switzerland (2 413 087 $/t HM) and the lowest for India (137 058 $/t HM). For India, cost data include only site selection, construction of the facility and R&D projects, and exclude waste immobilization, interim storage and transport. In the rest of the countries, similar costs estimates were obtained, i.e. in Lithuania (377 596 $/t HM) and in the Republic of Korea (543 639 $/t HM).

Comparing radioactive waste disposal costs per kW·h of electricity generated, the lowest costs were obtained for India (0.07 US cent/kW·h) and the highest costs for the Republic of Korea (0.23 US cent/kW·h). For Lithuania (0.97 US cent/kW·h) and Switzerland (0.51 US cent/kW·h), similar estimates were obtained.

The conversion rates provided in Table 6.17 were also applied for comparative assessment of CO_2 disposal costs in Lithuania and Cuba, presented in Table 6.18.

As one can see from Table 6.18, CO_2 disposal costs in Lithuania are 0.656 $/t CO_2 and 0.05 US cent/kW·h, and are similar to the estimates in Cuba: 0.732 $/t CO_2 and 0.06 US cent/kW·h, respectively. The lower disposal costs per t CO_2 and kW·h in Lithuania are related to higher CO_2 disposal capacity and the larger amount of electricity generated at the associated power plant during the life time period.

TABLE 6.16. COMPARATIVE ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL COSTS IN SELECTED COUNTRIES

Country	Imple-mentation	Evaluation method	Disposal concept	Total costs, Million $ (2010)	Amount of waste for disposal, t HM	Disposal costs/t HM, $ (2010)	Electricity generated during life time, million kW·h	Costs/kW·h, US cent (2010)
Lithuania	Planned	Based on study conducted	KBS-3V	3000	7945	377 596	307 900	0.97
Switzerland	Under implementation	Based on study conducted	Multibarrier concept	7763	3217	2 413 087	1 536 000	0.51
India	Planned	Based on study conducted	Multibarrier concept	1050	7661	137 058	1 592 000	0.07
Republic of Korea	Planned	Based on study conducted	KBS-3 V	19 571	36 000	543 639	8 545 000	0.23

TABLE 6.17. CONVERSION RATES APPLIED FOR COST ESTIMATES

Country	Conversion rates
Lithuania	1 LTL (2005)=0.359 $ (2010)
Switzerland	1 CHF (2006) =1.4344 $ (2010).
India	1 USD (2010)=1 $ (2010)
Korea	1 EUR (2006)=1.382 $ (2010)
Cuba	1 USD (2010)=1 $ (2010)

TABLE 6.18. COMPARATIVE ASSESSMENT OF CO_2 DISPOSAL COSTS IN LITHUANIA AND CUBA

Country	Imple-mentation	Evalu-ation method	Dispo-sal concept	Total costs, Million $ (2010)	Disposal capacity Million t CO_2	Disposal costs per t CO_2, $ (2010)	Electricity generated during life time period, Million kW·h	Costs/ kW·h, US cent (2010)
Lithu-ania	Research	Based on own assessment	Saline aquifer	14.1	21.5	0.656	29 380	0.05
Cuba	Research	Based on own assessment	DOGF	11.2	15.3	0.732	18 449	0.06

Note: DOGF – depleted oil / gas field

6.5. CONCLUSIONS

The main economic indicators for back end technology assessments include geological disposal costs per kW·h of the electricity produced per units of CO_2 and radioactive waste. The calculation methods vary for different countries and regions.

A wide variety of approaches were applied to perform radioactive waste disposal cost estimates. Cost studies have already been performed and published for the following radioactive waste repositories: Yucca Mountain in the USA; the final radioactive waste repository Olkiluoto and Loviisa in Finland; and Forsmark in Sweden. Costs were assessed for radioactive waste repositories in Belgium, Japan, the UK and a multicountry repository in the EU. The highest costs of final radioactive waste disposal are estimated in the USA, followed by Japan. The lowest costs are found in Belgium, Finland and Sweden.

Four countries have performed case studies on the costs of radioactive waste disposal in geological formations in the project presented in this chapter: India, Lithuania, Switzerland and the Republic of Korea. When comparing the total radioactive waste disposal costs for these countries with the total costs calculated for other countries presented and reviewed in the introduction to this chapter, one can notice that the total costs of radioactive waste disposal in Lithuania (2300–3000 million $) and Switzerland (7763 million $) are similar to the results from other European countries, especially for Finland (4122 million $) and Sweden (5728 million $). The lowest total radioactive waste disposal costs were obtained for India (1050 million $) and the highest for the Republic of Korea (19 571 million $), which are close to Japanese estimates (33 066 million $).

Comparing radioactive waste disposal costs per tHM across the countries covered in this chapter, one can notice that the highest costs were obtained for Switzerland (2 413 087 $/t HM) and the lowest for India (137 058 $/t HM). In other countries similar cost estimates were obtained, i.e. in Lithuania (377 596 $/t HM) and in Republic of Korea 543 639 $/t HM. The difference in costs is mainly related to the different economic developments and price levels in compared countries. The safety requirements and regulations are also different. The geological conditions and types of disposal also have an impact on disposal costs. Switzerland is an industrialized country having highest GDP/capita therefore higher disposal costs per t HM in comparison with India, Lithuania and the Republic of Korea.

The lowest costs per kW·h electricity were obtained for India (0.07 US cent/kW·h) and the highest costs were estimated for Lithuania (0.97 US cent/kW·h). The estimations for the Republic of Korea (0.23 US cent/kW·h) and Switzerland (0.51 US cent/kW·h) are in a similar cost range.

There is a wide cost range for CO_2 reported in the literature reviewed in this chapter, with the high cost scenario being up to 10 times more expensive than the low cost scenario. This is mainly due to differences in size and the natural properties of the disposal reservoirs (i.e. field capacity and well injectivity), and only to a lesser degree to uncertainties in cost parameters. Nonetheless, the following trends stand out based on the review of results of various studies summarized in the introduction to this chapter:

- Onshore saline aquifers are cheaper than offshore saline aquifers;
- Depleted oil and gas fields are cheaper than deep saline aquifers (even more so if they have reusable legacy wells);
- The highest costs, as well as the widest cost range, occur for offshore deep saline aquifers.

In the context of this CRP, only two countries presented estimates of CO_2 disposal costs: Lithuania and Cuba. However, these countries don't have actual plans for CO2 disposal, although it is a possibility for them. Both countries applied the same approach, which is the comprehensive methodology for CO_2 disposal costs assessment based on unit costs developed by the US EPA [6.19]. Although some CCD projects have been initiated in Switzerland and they are in the early stage of the feasibility assessment, they have not provided reliable costs assessment.

CO_2 disposal costs in Lithuania were assessed for the largest existing geological structure – the saline aquifer Syderiai. The total costs of CO_2 disposal in the Syderiai geological structure are 14.1 million $ (2010) and are similar to estimates obtained by Cuba – 11.5 million $, though depleted gas fields are considered in Cuba. The CO_2 disposal costs in Lithuania (0.656 $/t CO_2 and 0.05 US cent/kW·h) are similar to the estimates in Cuba (0.732 $/t CO_2 and 0.06 US cent/kW·h).

Comparing CO_2 and radioactive waste disposal costs per kW·h, one can notice that for almost all countries considered, except for India, radioactive waste disposal costs are higher. The comparatively low CO_2 disposal costs for Lithuania and Cuba are mainly due to limitations of the EPA methodology applied for cost assessments, as some country specific costs such as financial responsibility and administrative costs were not included in the costs estimates.

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Chapter 7

PUBLIC ACCEPTANCE

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7.1. INTRODUCTION

Radioactive waste, particularly the handling and disposal of radioactive waste, is one of the most disputed political and societal issues in many countries. Identifying factors relevant for public acceptance of the disposal of such waste is a challenge still to be solved [7.1]. Compared to the long standing controversy on radioactive waste, particularly on high level waste (HLW), CO_2 disposal is still a peripheral subject in most European countries.[2] Only a portion of the public is aware of this technology and risk perception is underdeveloped and unstable. The debate on CO_2 disposal and local resistance against a few (proposed) CO_2 disposal only began to impact on national CCD policies about four years ago in the cases reviewed in this chapter.

Although radioactive waste and CO_2 disposal differ in many aspects, they also share certain similarities. In particular, social acceptance is a critical resource needed to increase the chance of implementing disposal projects. Comparing the challenges and problems of social acceptance and the closely intertwined policies in both issue areas may facilitate mutual learning. A comparative analysis was performed for three countries: the Czech Republic, Germany and Lithuania. Special attention was given to public awareness and knowledge, public opinion, public and political debates, and policies.

This chapter is organized as follows: Section 7.2 presents the methodological foundations of the comparative analyses. Section 7.3 provides detailed analyses of public acceptance in the broader national context for the three participating countries. Finally, Section 7.4 summarizes the main insights from the national and cross-national assessments.

7.2. METHODOLOGY

The public perception of radioactive waste and CO_2 disposal was investigated and compared using qualitative and quantitative methods from empirical social research. The description of radioactive waste and CO_2 disposal in the Czech Republic, Germany and Lithuania was

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[2] Although the injection of CO_2 into geological formations is referred to as 'storage' in research and legislation about CCS, here the term 'disposal' will be used, describing the emplacement of CO_2 in an appropriate facility without the intention of retrieval.

predominantly based on qualitative analyses of literature and documents. Furthermore, quantitative analyses of empirical data from representative surveys were performed in order to describe the status of public awareness, knowledge and perceptions. Radioactive waste and CO_2 disposal were compared in the Czech Republic, Germany and Lithuania at an intra-national as well as at a cross-national level. For this purpose, criteria were established to allow a qualitative comparison. The national valuations of these categories are summarized in the comparative assessment table in Section 7.3.

7.3. COUNTRY CASE STUDIES

7.3.1. Czech Republic

7.3.1.1. Radioactive waste disposal

Status

The deep geological repository project is at the stage of repository siting (geological surveys in localities) and selecting a suitable locality. Siting is one of the basic objectives of the repository development programme. The site must satisfy requirements concerning rock properties, primarily isolating capacity and the ability to capture leaking radioactive substances, and a number of 'non-geological' requirements such as conflicts of interest, acceptability by the general public, the technical feasibility of the construction of surface facilities and site accessibility. Site selection for a future deep repository is governed by the 2002 document *Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic*, according to which two localities must be selected (a main and a reserve locality) that would provide the best geological conditions. The document *The Czech Republic's Land Use Development Policy* was approved by the government in 2008. It stipulates that two more suitable sites for deep repository construction are to be selected by 2015 with the involvement of the communities concerned. The basic principles regarding the position of local communities in the site selection process are:

- Geological investigation work and the possible construction of a deep repository must be beneficial for the communities concerned;
- Communities voluntarily participate in the site selection process;
- Communities must be provided with tools and powers to efficiently support their interests;
- The siting process must be transparent and democratic.

Risk assessment ('objective' risks)

According to the preliminary safety assessment, the risk associated with the construction and operation of the deep geological repository would be low.

Public awareness and knowledge

The vast majority of the Czech population has heard the terms 'radioactive waste disposal' and 'deep repository'. However, actual knowledge of these concepts varies greatly (cf. Fig. 7.1), as demonstrated by a poll taken in 2007 in six localities considered suitable for deep geological repository siting and in one locality that is not involved in any nuclear activity. Knowledge was shown to depend on whether respondents were directly involved in the process of siting and building the deep repository, whether they were residents close to the sites selected as possible locations or whether they were living far away from the sites.

Public opinion

The public opinion is that society should take care of the safe liquidation or disposal of radioactive waste and spent nuclear fuel (SNF) and that it should not defer the problem to future generations (cf. Fig. 7.2). However, the majority of respondents opposed the siting of the geological repository in their neighbourhood – often referred to as the 'not in my back yard' (NIMBY) phenomenon.

Figure 7.1 shows responses to the question: In your view, what is the method used today in the management of SNF and high level radioactive waste in the Czech Republic?

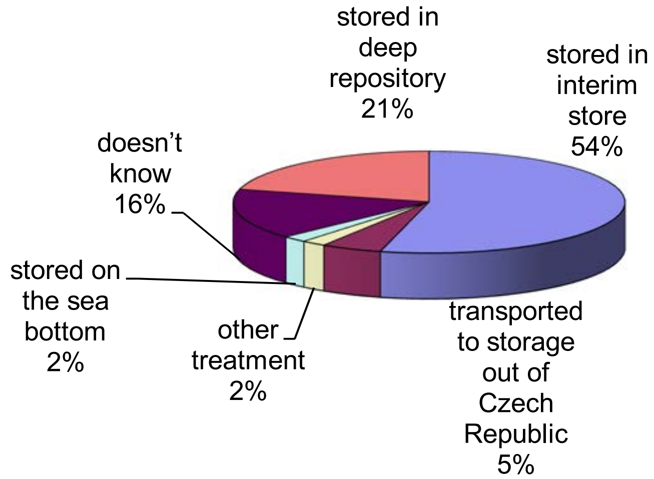

FIG. 7.1. Public knowledge about radioactive waste management in selected localities.

The general knowledge of the public about the methods used today in the management of SNF and high radioactive waste in general is shown by the responses to a related question in Fig. 7.2.

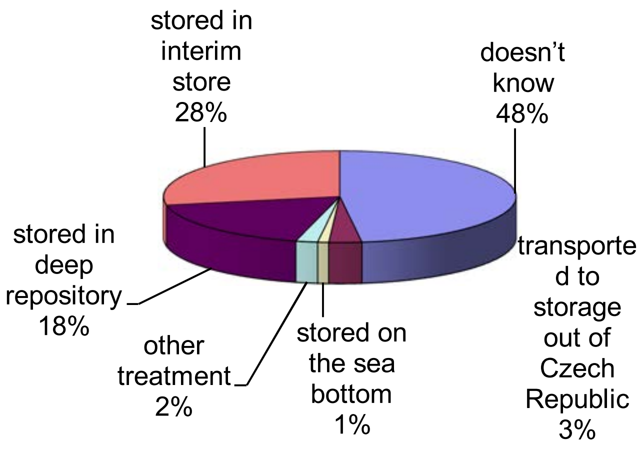

FIG. 7.2. General public knowledge about methods used for radioactive waste management.

A relatively better approach with respect to the NIMBY phenomenon was observed in communities where people had lived in the vicinity of a nuclear facility over a long period of time. However, it is not possible to conclude that all of the public opposition against the construction of a deep geological repository in their area or neighbourhood (approx. 90% of residents) can be explained by the NIMBY effect. This would be too simplistic and a somewhat problematic perception of resistance. There are various motives for the residents' refusal to accept a deep geological repository in their locality. Past events (seminars in the localities, public hearings) as well as public opinion surveys have shown great differences among the attitudes of individual localities as a whole, as well as among the citizens within these localities. Some representatives of the municipalities would – under certain conditions – agree to a geological survey in their territory, others remain strictly opposed. However, the residents of those municipalities whose representatives strictly opposed a survey often had diverse opinions or incentives. This provides opportunities for discussions and negotiations. Incentives must therefore be analysed and further dialogue and negotiations should be based on these findings.

Public debate and participation

Since its establishment, the Radioactive Waste Repository Authority (RAWRA) in the Czech Republic has striven to maintain good relations, particularly with the local population of areas close to operating repositories. Since the identification of sites, significant efforts have been devoted to facilitating a dialogue with local representatives and providing the local people with comprehensive information (public meetings, information leaflets, study trips to nuclear facilities and interim storage facilities, and visiting local representatives at nuclear sites and directly discussing issues of interest with them). Information is considered a necessary prerequisite for dialogue. Therefore, RAWRA began to support small communities, reconstructing local libraries and establishing small RAWRA information centres in several villages. Financed by RAWRA, these projects aim to facilitate the availability of up to date information on radioactive waste disposal as well as to substantially improve the operation of the libraries themselves.

Because RAWRA aims to achieve local support or tolerance at the sites where it will apply for the establishment of exploratory areas, it once again contacted the representatives of the six candidate sites. RAWRA proposed that it would cover the costs of consulting independent experts (nominated by the relevant communities) in an effort to critically review all activities to be carried out by RAWRA related to deep geologic repository development in the future. Moreover, these experts would be able to control the quality of activities and review the work from the perspective of local communities.

Significant progress has been achieved in the development of communication among stakeholders and public participation in the framework of the Arenas for Risk Governance (ARGONA) project in the 6th EU Framework Programme. A number of meetings took place in this context with representatives from various localities. The RISCOM[3] approach, which established a reference group of people from ministries, local politics, non-governmental organizations (NGOs) and experts from research organizations, was found to be very useful. It involved a debate, which could be considered a starting point for transparent discussion with people from potential sites for a deep geological repository. The experience gained in

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[3] The model, based on Habermas' communicative action and Stafford Beer's organizational theory, ensures that decision-makers and the public can validate claims of truth, legitimacy and authenticity.

the Czech Republic in the ARGONA project inspired an exchange of knowledge with partners in other countries using different participation methods. With the active participation of all the major stakeholders in the Czech programme, including the Minister of Industry and Trade, representatives of municipalities, NGOs and international experts, the international conference "Deliberation - The Way to the Deep Geological Repository" was held in Prague in November 2009. It further clarified the need for continued dialogue on the basis of what was developed in ARGONA. One of the main conclusions of this conference was that it was necessary to look for ways to create partnerships between communities in selected localities, NGOs and relevant state institutions.

Following this conference, roundtable discussions were held (involving all main stakeholders), aiming to establish a Working Group for Dialogue on the Deep Repository (June 2010). With the support of the Ministry of Industry and Trade, in cooperation with the Ministry of Environment (MOE), the working group was established in November 2010. Its main objectives were to define acceptable criteria for selecting a suitable locality for a deep repository and to establish a transparent process of deep repository siting that would adequately respect public interests. Activities of the Working Group include:

- Gathering and assessing the latest relevant domestic and international knowledge regarding the application of novel participatory and dialogue approaches;

- Issues relating to the implementation of the relevant legislative requirements;

- Reevaluation of the Concept of Radioactive Waste and Spent Nuclear Fuel Management;

- Reevaluation of the legislation and proposal of changes.

The Czech Republic participates in the project Implementing Public Participatory Approaches in Radioactive Waste Disposal within the 7th EU Framework Programme. This project aims to implement modern methods and approaches to ensure transparency and public participation in the management of radioactive waste and SNF. It is closely linked to the ARGONA project. One of the important activities is the application of various methods to ensure transparency and public participation in the national programs, radioactive waste and SNF in countries in the European Union (including the Czech Republic, Poland, Slovakia, Hungary, Romania, Slovenia, Bulgaria and others).

Resistance

In the period 2003–2008, about 25 local referenda were held on the topic of radioactive waste disposal. In all cases concerning the location of a deep geological repository, 80–99% of inhabitants voted against plans in the given location. Turnout ranged between 51% and 95% and was therefore above average compared to other referenda (total average turnout in local referenda in the Czech Republic is 58%). People feel distressed by the potential existence of a disposal site in their neighbourhood; they are afraid of the unknown and are concerned about enhanced radioactivity.

Considering the results of local referenda and the results of public opinion polls, it is clear that citizens of the Czech Republic, including those living in areas considered suitable locations for deep geological repositories, are aware of the necessity of resolving the issue of storing radioactive waste ‘here and now’. Despite this, they strictly object to the location of the repository in their region and oppose planning steps.

According to representatives of NGOs and to residents, there is another important reason why the overwhelming majority of citizens will always vote against a repository: as municipalities do not have a veto, residents fear that if they agree in principle they would have no influence on the siting process for a deep geological repository. Furthermore, they fear that they would not be able to withdraw from the process should they oppose the repository in the future. The level of information provided does not play an important a role in this case.

Local referenda in the Czech Republic therefore only have a manifestation nature because municipalities are in a position where they cannot decide themselves on the location of a deep repository. Referenda results could be somewhat different should municipalities have a stronger position in the area, as international experience proves.

7.3.1.2. Carbon dioxide disposal

Status

There is no concept for CO_2 disposal in the Czech Republic currently. Consequently, basic research (disposal capacity, rock formation, CO_2-rock-groundwater interactions, modelling) are conducted, and risk assessment baselines have been set up together with a public acceptance programme. The siting process and disposal facility development will follow EC Directive 2009/31/EU on CO_2 geological disposal, which has been included in the Czech legislation in June 2011.

Risk assessment (‘objective’ risks)

No safety assessment has been carried out for CO_2 disposal. However, on the basis of research from foreign projects, such disposal is expected to be safe and the risk low.

Public awareness and knowledge

The public is aware of climate change, although a portion of the public in the Czech Republic does not believe that the climate is changing or that the change is directly connected with CO_2 emissions. Moreover, a portion of the public does not understand the reason for CO_2 disposal or the disposal/retention process. Therefore, public awareness and knowledge is probably low. No research has been performed in this field in the Czech Republic.

Public opinion

According to experience from other fields (radioactive waste disposal, uranium mining, etc.), the majority of respondents is expected to initially oppose the siting of a disposal facility in their neighbourhood. A more positive opinion might be expected in communities with a direct connection to gas disposal or oil exploitation. However, in the absence of a CO_2 disposal project in the Czech Republic, community attitudes cannot be predicted. No research has been conducted on this topic in the Czech Republic to date.

Public debate and participation

As there are currently no CO_2 disposal projects and no region is being considered for siting, direct information and debate about CO_2 disposal in the Czech Republic barely exist. The EC

Directive 2009/31/EU is in the process of implementation in the country, but no detailed plans have been proposed for CO_2 disposal. Therefore, no local communities have been involved in debates about siting or development. Based on experience from other fields, the NIMBY (not in my backyard) effect would definitely evoke a local public debate. Such experience, particularly from radioactive waste disposal, should be used to concentrate efforts on communication with local communities and their representatives by focussing on mutual understanding and on providing comprehensive information to local people. Information should be considered a necessary prerequisite for dialogue on disposal issues.

Resistance

As there is no specific CO_2 disposal project, resistance is not an issue. However, in the general public and even among scientists, the motivation for CCD is misunderstood and there is a low level of knowledge about disposal. Therefore, resistance can be expected at the local level, not only in communities at a potential site but also in the vicinity of the site. People may believe that in different phases CO_2 could potentially leak from the disposal facility into aquifers and spread over long distances. People living in distant regions often fear the potential influence of CO_2 on their environment (water supply, etc.) and could therefore oppose the construction of facilities.

7.3.2. Germany

7.3.2.1. Radioactive waste disposal

Legal responsibilities

Due to the structure of the German political system, the licensing of a repository for high level radioactive waste is a complicated process that occurs at different political levels with many actors [7.2]. There is no central nuclear regulatory body in Germany [7.3], but one federal ministry has a strong administrative position: the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). BMU and its subordinate authority, the Office for Radiation Protection (BfS), are responsible for siting, planning, plant related research and development, exploration, construction, operation and decommissioning repositories. The Federal Ministry of Economics and Technology (BMWi) is responsible for the nuclear energy industry and repository related basic and applied research. The Institute for Geosciences and Natural Resources (BGR), a subordinate authority of BMWi, deals with the geoscientific issues of final disposal. The German Federal States act as agents for the federal government in the licensing process for final disposals. In this role, they have leeway to be restrictive in the licensing process, and they have access to other legal, institutional and political instruments to delay or even prevent a project. The licensing process also includes participation from local communities and the issuing of zoning permits. Public hearings allow the public to get involved [7.4]. The licensing process is, in principle, open to lawsuits both from individuals and organizations, which when successful, can prevent the construction and commissioning of disposal facilities. This is often the case due to complexities of the planning and authorization process.

Radioactive waste

According to the EURATOM (European Atomic Energy Community) Treaty, special fissile materials are the property of the European Union, and Member States have the right to use this material. According to German Atomic Law, spent fuel had to be reprocessed before

1994, both reprocessing and direct disposal were allowed between 1994 and 2005, while after 2005 the direct disposal of spent fuel is the only permissible option. In Germany, radioactive waste is divided into waste with negligible heat generation (low and medium level waste, which will amount to about 277 000 m^3 by 2040, and contains 1% of the total radioactivity) and heat generating waste (high level waste, which will amount to approximately 22 000 m^3 by 2040, and comprises about 99% of radioactivity) [7.5]. (Note that nuclear phase-out will reduce these estimated amounts.)

The Konrad mine (Lower Saxony) for low and medium level waste is the first approved final repository according to the German atomic law [7.6]. Disposal is due to start in 2014 provided that the start-up processes run smoothly. High level radioactive waste is currently stored in 13 decentralized interim storage facilities at nuclear power stations**.** High level and other radioactive waste is also stored at the decentralized interim storage facilities in Greifswald (Mecklenburg-Pomerania) and Jülich (North-Rhine Westphalia) as well as in the central interim storage facilities in Gorleben (Lower Saxony) and Ahaus (North-Rhine Westphalia) [7.7].

Policy and public opinion about nuclear energy

From the 1950s to the 1970s, civilian nuclear energy was perceived in Germany as *the* innovative energy technology, and public and political support was high. About 35 years ago, the situation began to change, and a national anti-nuclear movement evolved from grassroots activities against a nuclear power project in an agricultural area. After the Chernobyl accident in 1986, public support for nuclear energy declined significantly, and the party consensus on nuclear energy began to break up. The Social Democrats, former nuclear enthusiasts, and the new Green Party opposed nuclear energy, whereas the Conservatives and Liberals supported nuclear energy as a ‘transition’ technology. In 2002, the Social Democrat/Green government changed the Atomic Law to phase out nuclear energy by about 2022. The Conservative/Liberal government changed that law again in 2010 to extend the lifetime of nuclear reactors as a ‘bridge’ to a ‘renewable future’. The last reactors were supposed to produce electricity until about 2036. However, the accident at the Fukushima Daiichi NPP in March 2011 broadened and solidified the anti-nuclear attitude. It did not change the ‘objective’ safety status of German reactors, but it did change the perception of nuclear safety. Therefore, the Conservative/Liberal government made a U-turn in March 2011 (despite some resistance in their parties) and, in conformity with the public at large and the overwhelming majority in Parliament, it ordered to shut down the seven oldest reactors and announced that nuclear power would be phased out by 2022. This policy became law in August 2011 when the Atomic Law was amended [7.8]. The majority of politicians and the public regard the phase-out as getting rid of an energy policy ballast. Nevertheless, as shown by a recent study [7.9], one of the consequences of the phase-out is expected to be increased CO_2 emissions from the power generation sector. Therefore, keeping in mind the climate protection targets of the German government, households and industry will have to increase their CO_2 reduction efforts at an increased cost.

During the long process of policy formulation, public opinion on energy related topics has had a considerable influence on political decision making. In the polls, renewable energy technologies have a high level of public support, whereas the public acceptance of coal fired power plants has plunged, despite the climate change debate. It is now close to the low level of acceptance that characterizes nuclear energy [7.10]. For many years, surveys have indicated that German citizens are exceedingly sceptical about nuclear energy, particularly compared to other countries [7.11]. Even the CO_2 reduction policy has not modified this attitude substantially [7.12]. However, there is still a lack of research on this particular issue [7.13]. After the Fukushima accident, the support for nuclear power in Germany dropped further to only about 20%, one of the lowest figures worldwide [7.14]. The 2011 nuclear policy shift reflects this broad and stable anti-nuclear public attitude.

Search for a final repository for radioactive waste

Surveys indicate that the unresolved final disposal problem is a major factor impeding the acceptance of nuclear energy [7.15], [7.16]. Whether solving this problem will result in a higher acceptance of nuclear energy as previously assumed [7.17] cannot be predicted with certainty [7.16], but it seems unlikely after Fukushima. Furthermore, Germany has a long way to go to find such a solution if a working HLW final disposal facility is considered the solution.

For about 30 years, the unexcavated Gorleben salt dome has been investigated for its suitability as a final repository for high level radioactive waste. In 1983, the Federal Institute for Physical Technology (the predecessor of BfS) concluded in a (disputed) report that the Gorleben dome will most likely be deemed suitable, and the below ground investigations began in 1984. However, from the outset, efforts to develop Gorleben led to a 'political paralysis' due to the polarization about nuclear energy issues in general, the widespread national opposition, the manoeuvring of political actors at the federal and state levels, litigation and the continuing debate on the suitability of the salt dome [7.4], [7.18]. The federal SPD/Green government interrupted the underground exploration in 2000, but in 2010 the CDU/CSU/FDP government lifted the moratorium. This move fuelled protests once again, and the focus of anti-nuclear campaigning was shifted back to Gorleben.

Almost all political parties are well aware of the necessity of disposing of high level radioactive waste in a geological formation. Despite this, the opposition against the Gorleben project remains unchanged and the prospects for the project are dim. However, proposals for a 'reset' (an open nationwide search for a suitable radioactive waste disposal within Germany, also taking granite and clay formations into account) are heard from political actors, including state governments with potential disposal sites. Alternatives have also been proposed, such as interim 'surface final disposal' for up to 150 years and even a retrievable final underground disposal, which would represent a deviation from the Gorleben concept and the disposal policy in general. Nevertheless, the debate is just starting and it is far from unanimous, because acceptance of a disposal facility is still low everywhere: only about 30% of the population would accept their region being proposed [7.19]. Furthermore, the question of what geological formations are suitable is still contested, as are the criteria for selection and the form of the decision making process. Political outrage is therefore not only associated with the subject (radioactive waste), but also with the governance of the policy process [7.4]. One attempt to develop a selection procedure for a final disposal facility, proposed by the Working Group for Selection Process for the Final Disposal Sides (Arbeitskreis Auswahlverfahren Endlagerstandorte (AkEnd) [7.20] working on behalf of BMU, petered out in the political process because it was vigorously contested for different reasons (e.g. because it proposed one disposal procedure for all types of radioactive waste, the proposed selection process was perceived to be too time consuming).

The nuclear phase-out offers an opportunity to debate the disposal issue in a more factual way. The production of new spent fuel is due to stop in the foreseeable future, and the nuclear phase-out meets the central demand of the anti-nuclear and anti-disposal movement. Therefore, high level radioactive waste disposal is no longer 'a proxy battle' [7.21] for nuclear energy. This battle seems to be over in Germany – at least as long as phasing out nuclear energy does not jeopardize the stability of the electricity grid or the affordability of electricity supply. Moreover, a new EU directive is exerting pressure on the political process. This directive was adopted in July 2011 [7.22] and creates a framework with obligations for the EU Member States: national programmes for the construction of disposal facilities must be prepared by 2015, including timetables, implementation plans, cost assessments plans, etc. The European Commission will examine these programmes and can demand changes. The public must also be given opportunities to participate effectively in the decision making process. Therefore, changing the national and transnational framework will offer an opportunity to facilitate a new process for finding a high level radioactive waste final disposal site, which is based on agreed criteria, and is scientifically sound, transparent and participatory. Even the 2002 selection procedure mentioned earlier may be revived but rapid results are not to be expected. More research is needed, and the controversy about a suitable location and local resistance against any proposed disposal facility will continue.

7.3.2.2. Carbon dioxide disposal

Legal responsibilities

In 2009, the European Union CCS Directive entered into force [7.23] as the legal regulatory framework for CCD. Germany was supposed to incorporate the EU Directive into national law by 25 June 2011[4]. As the EU Directive allows Member States to decide whether they would like to apply CCD, the national framework is of importance. Due to the federal structure of Germany, the consent of both the Lower House (Bundestag) and the Upper House (Bundesrat) is required, granting the federal states a strong influence on legislation. This two layer polity still blocks the implementation of the EU directive in law and has led to a CCD policy impasse: the Upper House refuses to agree to the CCD law proposed by the Lower House. As a consequence, the EU Commission began to start an infringement procedure against Germany in July 2011.

Disposal project

There is one CO_2 disposal research project in Germany: the Ketzin (Brandenburg) project CO_2SINK (until 2010) and its follow-up project CO_2MAN, coordinated by the German Research Centre for Geosciences. The project partners include E.ON, Vattenfall and RWE. CO_2 from Vattenfall's 30 MW(e) pilot plant for CO_2 capture at the lignite fired power plant at Schwarze Pumpe is injected. Vattenfall planned to operate a 300 MW(e) lignite demonstration power plant (oxyfuel and post-combustion capture) at Jänschwalde (Brandenburg), separating about 1.7 Mt CO_2 per year and injecting it into a demonstration disposal facility. The plant was supposed to be operational by 2015 to receive EU funding. Vattenfall received authorization to explore the suitability of two regions in Brandenburg as disposal sites. However, due to the failure to implement the EU directive in Germany, Vattenfall decided in December 2011 to discontinue the Jänschwalde project.

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[4] After the completion of the report the majority of the Bundesrat and the Bundestag agreed in July, 2012 on a modified CCS law. But this restrictive law darkens the perspectives of CCS in Germany further, at least for the foreseeable future.

Public discussion about CCD and the CCS Directive

There is an intensive debate about the role CCD should play in the future energy system and how to cope with the increasing lack of social acceptance of CO_2 disposal projects [7.24]. Public acceptance is an important precondition for the large scale deployment of CCD, as the FENCO-ERA-projects emphasized already in 2010. Against this background and under the auspices of BMU and BMWi, preparations started in late 2008 for a German CCD law. The federal cabinet of the grand coalition (Conservatives and Social Democrats) approved a first draft in April 2009, which transferred the content of the EU directive into German law largely unmodified. A public discussion and a parliamentary debate began soon after and, although some feedback was positive, criticism was also widespread. In addition to the general opposition to CCD, criticism of the content of the law included whether the law should be permanent or limited in time; whether it should regulate CCD in general or only the disposal of CO_2, and whether it should limit the volume of CO_2 disposal. Furthermore, northern federal states with the biggest disposal capacity (in particular Schleswig-Holstein and Niedersachsen with Conservative/Liberal governments) came under pressure from anti-disposal movements supported by NGOs, feared that leakages and health problems, pollution of drinking water and depreciation of property. These federal states threatened to block the federal law in the Bundesrat. This growing resistance overlapped with the federal election in September 2009, and the draft law was therefore withdrawn. In October 2009, the new government coalition (Conservatives and Liberals) announced the prompt implementation of a CCD law, and the importance of winning public acceptance for CCD was explicitly mentioned.

In March 2010, the coalition resumed work on a modified law, and the amended version of the law (July 2010) took into account former criticism partly. It became a limited CO_2 disposal demonstration law, restricting the volume of CO_2 disposal to 3 Mt CO_2 per disposal facility and 8 Mt nationwide (per year). However, this version was also contested both in politics and society. In particular, the opposing northern federal states demanded a provision providing them with the opportunity to prevent disposal projects (‘state clause’).The federal government subsequently prepared a third version of the law, with a first version of a state clause in early 2011. The same federal states opposed the amended version yet again, demanding a more specific, legally secure clause. Finally, in an effort to secure consent, the federal government modified the law again (May 2011). The new clause appeared to satisfy the anti-CCD federal state majority, but met with resistance both from states with a pro-CCD policy and from political and societal forces that totally opposed CCD.

In July 2011, the Conservative/Liberal majority in the Bundestag passed the law. However, in September 2011 the draft law found no majority in the Bundesrat. Various federal states opposed for different reasons: the coal dependent federal states Brandenburg (with a Social Democrats/Left government that has an *explicit* pro-CCD policy) and Saxonia (Conservative/Liberal government), together with Hamburg (Social Democrats government) where a new coal fired power plant (potentially with CCD) is being built, opposed the state clause. Other federal states, governed by diverse coalitions of Social Democrat, Green and Left party ministers, opposed partly because the restriction on CO_2 disposal did not go far enough or because they did not agree with specific provisions (in particular, the question who should operate closed CO_2 disposal sites: the state or the companies that fill the disposal sites) Yet other states opposed because of political tactical reasons (to disgrace the federal government). The federal government appealed to the mediation committee, but the negotiations ended without any results. German CCD policy is thus left empty handed and remains blocked. Even the threat of legal action by the European Commission against Germany because it has failed to implement the directive has not mobilised German policy. Without a CCD law providing a sound legal basis for demonstration projects, the future of CO_2 disposal projects in Germany looks bleak.

Public awareness and perceptions of CCD

In contrast to nuclear power, CCD technologies are largely unknown among the general public. In a representative survey carried out in 2009, 62% of the German population indicated that they had never heard of CCD [7.25]. Only 21% of German citizens knew that CCD can help reduce global warming.

Due to the low level of CCD awareness, the average status of attitude formation among the general public differs between nuclear energy and CCD. With respect to nuclear energy, a process of attitude formation has already taken place and public opinion regarding nuclear power stations and HLW disposal are highly stable. Regarding CCD, however, the attitude formation process among the general public is still only at the beginning. (This does not apply to environmental NGOs that are actively involved in the CCD debate.) Thus, in the present situation, public opinions regarding CCD are mostly initial perceptions of lay persons which are neither based on knowledge nor on conviction [7.26]. Therefore, public perceptions of CCD are currently highly unstable and can be easily changed by contextual information or slight changes in mood [7.27].

In general, CCD technologies are initially assessed neutrally by the German public [7.28]. However, initial perceptions vary between men and women and between regions [7.10]. Men evaluate CCD more positively than women. Furthermore, CCD is initially perceived more negatively in Schleswig-Holstein, which is the German region with the largest capacities for CO_2 disposal, as well as in the Rheinschiene, which is region where the Huerth RWE demonstration power plant was planned.

Initial perceptions of CCD also vary with regard to the respective process step. Whereas capture is initially negatively evaluated by 29% of the German population, transport is negatively evaluated by 48% and disposal by 49%. Accordingly, German citizens perceive personal risks of CO_2 disposal to be higher than personal risks associated with CO_2 transport or capture [7.28]. Additionally, personal risks associated with all three process steps are perceived to be higher by women than by men. Thus, it can be assumed that different risk perceptions are one important reason for the varying initial perceptions of CCD between men and women.

Regionally, disposal and transport risks are also evaluated differently: personal risks associated with CO_2 disposal are perceived to be higher in Schleswig-Holstein than in Rheinschiene, whereas the risks associated with CO_2 transport are perceived to be higher in Rheinschiene than in Schleswig-Holstein. With regard to CO_2 capture, the risk perceptions do not differ between inhabitants of Rheinschiene and Schleswig-Holstein.

One important similarity between public opinions on or perceptions of HLW and CO_2 disposal is that both are heavily influenced by risk perceptions. However, whereas the risk perceptions of HLW disposal and opinions on nuclear energy are generally highly stable among the German public, it can be assumed that risk perceptions of CO_2 disposal have not yet fully formed. Therefore, information on risks (and benefits) of CO_2 disposal should be relevant, balanced and comprehensible for lay persons in order to avoid misconceptions of the associated risks and thus prevent risk perceptions that cannot be changed later.

To summarise, in Germany, nuclear energy and radioactive waste are associated with a 'dread risk', which elicits feelings of uncontrollability, catastrophe and imposed risk. From the public's perspective, the delay in making decisions on radioactive waste disposal is considered confirmation that there is no safe way of disposing of this waste [7.16]. Nevertheless, now that a decision has been made to phase out nuclear power, there is a chance that the final disposal debate could be reopened.

In contrast, the debate about CCD is less intense and politically less relevant from a national perspective. Yet, in some areas with the potential for a CO_2 disposal project, the risk perception of a substantial proportion of the population may be gridlocked – an assumption for which empirical evidence is still required. With the (failed) implementation of the EU directive, CCD became the focus of a broader controversial national debate. Here, the radioactive waste debate appeared to influence the risk perception of CO_2 disposal: CCD critics draw a parallel between the high risks of radioactive waste and CO_2 disposal, and scrutinize the concept of geological barriers, which has been transferred from radioactive waste disposal to CO_2 disposal. The tightness of barriers over decades or more is questioned in general. However, even if German politics reaches a compromise for a CCD law, CCD technology may play a very limited role in Germany because of the focus on renewables and natural gas – at least for the foreseeable future. This may restrict demand for CO_2 disposal areas and hence the potential for widespread societal conflicts.

7.3.3. Lithuania

7.3.3.1. Radioactive waste disposal

Legal responsibilities

There is a quite complex net of responsibilities in the sector of radioactive waste disposal in Lithuania. Licensing the construction and operation of a repository is the responsibility of the state enterprise Radioactive Waste Management Agency (RATA). RATA was established to implement the management and final disposal of all radioactive waste generated by the Ignalina NPP during its operation and decommissioning, and the radioactive waste from small producers (hospitals, industry, research institutions etc.). Existing disposal facilities do not conform with the requirements and standards for the repositories and cannot be used for final disposal of radioactive waste. It is RATA's task to construct and operate the repositories for short lived and long lived radioactive waste.

Upon implementation of provisions set forth by the Law on Radioactive Waste Management, the Government of the Republic of Lithuania issued the Resolution No. 1487, dated 27th December, 1999, by which the Ministry of Economy was entrusted to set up the radioactive waste management agency. RATA functions in accordance with the Strategy of Radioactive Waste Management approved by the Government of the Republic of Lithuania. On the course of its activities, RATA shall observe the Law on Radioactive Waste Management, the Law on Nuclear Energy, the Law on Radiation Protection, the Law on State and Municipality Enterprises, and other legal acts of the Republic of Lithuania. As management of the radioactive waste is directly related with nuclear and radiation safety, RATA's activity shall be licensed by the regulatory bodies, namely the State Nuclear Power Safety Inspectorate (VATESI) and the Radiation Protection Centre.

The Ministry of Energy, established in 2009 from several energy related departments from the Ministry of Economy, is responsible for the nuclear energy industry and repository applied basic research. The Laboratory of Engineering Problems of Nuclear Energy at the Lithuanian Energy Institute deals with the main engineering issues of final radioactive waste disposal. The Geological Survey of Lithuania is responsible for geoscientific issues associated with radioactive waste disposal. The licensing process also includes local communities, and the issuing of zoning permits. Public hearings allow the public to get involved.

Radioactive waste

Some 22 000 nuclear fuel assemblies, an equivalent of approximately 2500 t of uranium, were used at the Ignalina NPP throughout its operation. All of these assemblies must be stored for about 50 years and then disposed of. In order to manage and dispose of SNF and long lived radioactive waste from the Ignalina NPP, a deep geological repository is planned to go into operation in 2041. Several potential geological formations for long lived high level radioactive waste disposal have been investigated: crystalline basement, clay, anhydrite, etc. Research conducted in recent years has shown clay and granite type crystalline basement formations to be the most suitable. The best prospects for a crystalline basement appear to be in the south-east of Lithuania, where the basement rocks are covered by a relatively thin (200–300 m) sedimentary layer [7.29], [7.30], [7.31].

The disposal concept in Lithuania for SNF from the RBMK-1500 reactors in crystalline rocks is based on the Swedish KBS-3 concept whereby SNF is placed in copper canisters (casks) with a cast iron insert [7.32], [7.33], [7.34]. Bentonite or a mixture of bentonite with crushed rock are also foreseen as a buffer and backfill material. Taking into account the results of the criticality, dose rate assessment and thermal calculations, it was proposed that 32 half-assemblies of the SNF be loaded into one disposal canister. Based on preliminary assessment, the reference canister would have a diameter of 1050 mm and a length of 4070 mm. For the disposal of the Lithuanian SNF, about 1400 canisters would be required [7.35].

Currently, HLW is stored in decentralized interim storage facilities at the Maisiagala and Ignalina NPPs. These locations were originally intended as final repositories, but their present status created doubts about their safety level. Preliminary investigations at the Maisiagala repository have shown that radionuclides could possibly migrate from the repository [7.36]. The design work of the near surface radioactive waste repository started in 2009 and construction started in 2012. The facility is to be commissioned in 2015. The costs of the project are estimated between € 100–200 million and will be covered by the European Bank for Reconstruction and Development and the European Commission.

Public opinion about nuclear energy

One specific risk perception study related to nuclear energy has been conducted in Lithuania: “Risk perceptions, public communication and innovative governance in knowledge society” (RINOVA), which was funded by the Lithuanian State Science and Studies Foundation [7.37]. The representative population survey (N=1000) was conducted in June 2008. A standardized questionnaire on public perceptions of nuclear power, radioactive waste disposal climate change etc. was prepared. The main questions addressed in the survey were:

- What social and environmental concerns are reflected in nuclear risk perceptions?

- What symbolic meanings of nuclear power are reflected in public attitudes?
- How are nuclear risks associated with the operation and radioactive waste disposal perceived among other threats?
- How does the public reflect upon participation and responsibility issues regarding nuclear power issues?

Almost 30% of the respondents were totally in favour of nuclear energy development in Lithuania. More than 90% of respondents believed that scientists and the government should be responsible for nuclear energy issues. 45% of the respondents believed that most scientists were not certain whether nuclear energy is safe.

Surveys over a number of years have indicated that the Lithuanian population, in comparison to other European countries, is in favour of nuclear energy. The 2008 and 2005 Eurobarometer survey conducted in 27 EU Member States indicated that the level of support for nuclear energy varies strongly from country to country [7.38], [7.39]. However, citizens in countries with operational NPPs were found to be considerably more likely to support nuclear energy than citizens in other countries**.** That there is a strong link between these two variables – support for nuclear energy and existence of NPPs in one's country – is clearly emphasized by the fact that most countries with an above average strong support for nuclear energy actually had NPPs. The strongest support (about 60%) was found in the Czech Republic and Lithuania, as well as in Hungary, Bulgaria, Sweden, Finland and Slovakia[5] [7.38], [7.39]. Another Eurobarometer survey conducted in 2010 [7.40] indicated that the unresolved final disposal problem for radioactive waste is a major factor impeding the acceptance of nuclear energy. 73% of Lithuanian residents believed that NPPs can be operated in a safe manner; in the 2006 survey this figure was 69%.

The joint Lithuanian–British market research and public opinion survey company *Baltic Surveys* was commissioned by the Lithuanian State Nuclear Power Safety Inspectorate to conduct a representative survey of Lithuanian residents in October–November 2009. Over a thousand people aged between 15 and 74 years living in the country were surveyed. More than half of Lithuanian residents agreed with the statement that disposal (56%) and transportation (59%) of radioactive waste is safe. Should a radioactive waste disposal facility be constructed, residents would be concerned about the impact on their health and the environment (37%), in particular about the release of radioactive waste from the disposal facility into the environment (36%). Lithuanians are less concerned about the possible deterioration in the attractiveness of the district for business development (3%) and the huge costs for the construction and operation of the disposal facilities (1%).

As compared with 43% of respondents in 2006 who agreed with the statement that the legal framework in Lithuania adequately assured nuclear safety, in the survey in 2009, this number was as high as 52%. 50% of residents tended to think that the nuclear safety authority sufficiently regulated the safe operation of nuclear installations. In 2006, such opinion was held by 47% of the respondents. However, 66% of respondents felt insufficiently informed about nuclear safety issues in Lithuania (in 2006, this figure was 82%) and only 25% felt sufficiently informed about these issues. Lithuanian residents pointed out that they need brief and understandable information about the methods of disposing of radioactive waste, where

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[5] Other countries which did not participate in the CRP are here also mentioned for the purpose of comparison.

and how those facilities are to be constructed, what the current impacts of the Ignalina NPP are on their health and what impacts could be expected in the foreseeable future.

Public opinion and understanding the safety aspects of nuclear power facilities are very important. Information on regulatory activities should be made more accessible and easy to understand. 50% of respondents thought that the Lithuanian State Nuclear Power Safety Inspectorate (VATESI) sufficiently regulates nuclear safety in Lithuania, 14% of the respondents believed that regulation and supervision was unsatisfactory.

Public opinion about radioactive waste disposal

The 2008 Eurobarometer survey "Attitudes towards radioactive waste" indicated that 35% of Lithuanians (41% of Europeans on average) *totally* agree that there is no safe way of getting rid of high level radioactive waste, while just 30% of Lithuanians (31% in EU) *tend to* agree [7.39]. In Lithuania, 21% disagreed (14% in EU) did not know or had no opinion. The opinion that there are safe ways of getting rid of high level radioactive waste was relatively strong in a set of countries that have NPPs in operation: the Netherlands, the Czech Republic, Hungary, Slovenia, Slovakia, Lithuania and Belgium. In Lithuania, 21% disagreed with this statement. To summarize, the survey demonstrated that a higher level of knowledge lowers risk perception, leading to a higher level of acceptance of nuclear energy. The idea that there is no safe way of getting rid of high level radioactive waste had slightly more support in Finland in 2008 than in 2005, while Cypriot, Lithuanian, Hungarian, Latvian and Dutch respondents appeared to have become more convinced of the opposite, i.e. that there actually is a safe way of getting rid of it.

When analysing differences at the country level, the most striking result is that the potential effects on the environment and on health associated with a disposal site for radioactive waste are considered to be the most worrying aspect of having such a site near one's home in all countries polled**.** Public opinion appears to be rather homogenous in the case of the second issue: the risk of radioactive leaks ranks second as the most worrying aspect of radioactive waste disposal in all EU countries except in Sweden. In the hypothetical situation, mentioned above, the impact on the environment and health would worry up to three quarters of Lithuanians.

There is a wide consensus at the country level that respondents would like to be directly consulted and would want to participate in the decision making process if an underground disposal site for radioactive waste was to be constructed near their home. Absolute majorities of citizens in 15 EU countries are of this opinion, in another 11 countries relative majorities agree, and in only one country, Lithuania, does a minority agree. The largest segment of Lithuanian respondents would rather leave it to responsible authorities to decide on the construction of a disposal facility.

The idea that responsible authorities should decide on a disposal site for radioactive waste is supported by Lithuanian, Czech and Slovak respondents in particular. The trust in information from NGOs on radioactive waste management is highest among Swedish, Slovakian, French and Danish respondents. In Lithuania, Bulgaria and Estonia, respondents are least likely to trust NGOs to provide them with trustworthy information on this topic.

It appears that over 50% of the Dutch, Belgian, Lithuanian, British, French, Slovenian and Finnish opponents of nuclear power would change their view regarding nuclear energy production if a safe solution to managing radioactive waste were to be found. The perception that deep underground disposal is the most appropriate solution for the long term management of these materials is accepted by 45% of respondents, whereas 38% reject this.

The RINOVA study indicated the positive symbolic meaning that dominates the public perceptions of NPPs in Lithuania, and it revealed that economic and energy security concerns have priority whereas radioactive waste disposal problems ranked second. Involvement of the Lithuanian society is not perceived as important (just 44.1% of respondents believed that society is responsible for nuclear energy issues including safety and radioactive waste disposal). It therefore has no responsibility or legitimized power to participate in nuclear power regulation issues. There is little difference between public perceptions of an old and a new NPP. Nuclear energy, including the radioactive waste disposal problem, was rated as a medium threat (3.52) by respondents asked to evaluate their perception of threats on a scale of 1 (low) to 5 (high). The highest threat for Lithuanians was related to food preservatives.

The necessity to dispose of high level radioactive waste in deep geological formations is obvious. However, there is still much debate in society and at all political levels regarding the suitable host rocks, the criteria for selection, sites for such a disposal facility and the form the selection (decision making) process itself should take.

7.3.3.2. Carbon dioxide disposal

Legal responsibilities

There are no national laws regulating CO_2 disposal in geological formations in Lithuania, but the related EC Directive had to be implemented by 25 June 2011 [7.41]. Implementing this directive required amending other EU directives and regulations that had already been implemented in Lithuanian law: Directive 85/337/EEC of 27 June 2005 on the assessment of the effects of certain public and private projects on the environment (Environmental Impact Assessment Directive); Directive 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy; Directive 2001/80/EC on limitation of certain pollutant emissions from large combustion power plants; Directive 2004/35/EC of 21 April on environmental liability with regard to the prevention and remedying of environmental damage; Directive 2006/12/EC on waste; Directive 2008/1/EC concerning integrated pollution prevention and control and regulation on shipments of waste; and the CCS Directive 2009/31/EC to be transposed in Lithuanian laws by making amendments and passing a new law on 25 June 2011. The main legal acts that had to be amended to implement the requirements of directive were: Waste Management Law (1998); Law of Earth Entrails (1995); and Law on Environmental Impact Assessment (1996).

Possible disposal projects in Lithuania

There are no CCD demonstration projects in Lithuania, but there are three potential geological aquifer structures in the south-west of Lithuania suitable for structurally trapping CO_2: Vaskai (8.7 Mt CO_2), Syderiai (21.5 Mt CO_2), D11 (11.3 Mt CO_2) which together can store 41.5 Mt CO_2 [7.42], [7.43]. In Lithuania, ten oil fields are presently being exploited. The size of the oil fields ranges from 16 000 tons to 1 400 000 t of recoverable oil. The disposal potential of the largest oil field in west Lithuania is 2 Mt CO_2. In total, the amount of CO_2 that could potentially be stored in oil fields in Lithuania is estimated to be very low at 7.6 Mt CO_2 compared to 20 Mt of average annual CO_2 emissions in Lithuania.

Public discussion about CCD and the CCS Directive

There have been no public debates in Lithuania regarding the national framework to implement the EC Directive on CO_2 geological disposal. Therefore, no decision has been made on national policy related to the role CCD should play in a future energy system or in relation to CO_2 disposal approval procedures, organization and control.

Public awareness and perceptions of CCD

No specific studies on public awareness or CCD acceptance have been conducted in Lithuania. In order to get more information on the perceptions of a wide range of stakeholders on the potential role of CCD in the EU, a team of researchers performed a survey of more than 500 stakeholders within the framework of the EU funded ACCSEPT1 project [7.44]. During 2006, stakeholders from the energy industry, researchers, government officials, parliamentarians and environmental associations from 28 European countries participated in this survey. Important questions were:

- Is CCD geologically feasible within the EU and what disposal capacities are available?
- Can the risks of CCD be appropriately assessed and managed?
- Can CCD be undertaken under existing international and European law?
- Is the information on the costs of CCD good enough to make robust decisions?
- What policies can help to make CCD economically more feasible?
- Is CCD acceptable to European stakeholders and to the European public?
- Is there sufficient fossil fuel to make investment in CCD worthwhile in the long term?
- How large are the externalities arising from CCD and how important are they?
- Will investment in CCD detract from the development and deployment of other zero and low carbon energy sources?

It was found that the majority of respondents was moderately supportive of CCD and believed that it had a role to play in their own country's plans to mitigate CO_2 emissions. Their belief in the role of CCD tended to increase when moving from the national to the EU to the global scales. 44% of the sample did think that there might be *some* negative impacts arising from CCD for investment in other low or zero carbon energy technologies, compared to 51% who did not think that there would be *any* negative impacts or thought that impacts might even be positive. Stakeholders from the energy sector strongly supported the development of CCD technologies, though potential adverse impacts for renewables were acknowledged. Environmental NGO respondents were much more concerned about the risks and the implications for renewable energy than energy industry and governmental stakeholders. Respondents from Norway, the UK and the Netherlands were the most enthusiastic about CCD and least concerned about the potential risks, possibly because offshore projects are more likely. Other countries, including Lithuania, were less enthusiastic about CCD and tended to regard the risks to health, safety and the environment as being greater. They also believed that there would be more negative impacts on the development of other low carbon technologies and decentralized power generation. Most other counties reflected a position between these two groups.

The main results were:

- For 75% of the respondents, CCD was 'definitely' or 'probably' necessary for large scale CO_2 reduction;

- 90% of the respondents believed that research, development and demonstration were the most appropriate next steps for taking CCD forward in their country;

- For more than 85% of respondents, incentives for CCD should be applied Europe wide;

- The majority of respondents thought that the risks associated with CCD were 'moderate' or 'minimal';

- 44% of the sample believed that the development of low and zero carbon technologies would suffer from investments in CCD;

- The public was 'moderately supportive' (34%) in own country, followed by 'neutral' (30%); 'moderately opposed' (19%); 'strongly opposed' (4%) and 'strongly supportive' (5%);

- The public was more supportive of CCD at the EU scale than in their own countries. North-west Europe and southern Europe were keener on CCD in their own countries than Central and Eastern Europe (including Lithuania) and Scandinavia;

- A smaller role was played by CCD in national debates in Central and Eastern Europe, including Lithuania;

- The risk perceptions of CCD were greatest for Central and Eastern European countries, including Lithuania;

- Central and Eastern Europe, including Lithuania and Scandinavian countries, were more likely to regard CCD as having a negative impact on decentralization and renewables;

- The group of countries with low GDP per capita (< $ 19 000 per annum), including Lithuania, was generally less enthusiastic about CCD than the other groups, and perceived it to be a less important component of the national climate change debate;

- The group of countries with low GDP per capita, which included Lithuania, were less keen on EU Emission Trading System with tighter national caps and on post-Kyoto requirements;

- The group of countries with low GDP per capita perceived the risks of CCD to be higher than other groups and perceived more negative impacts upon decentralization and energy security;

- Central and Eastern Europe, including Lithuania, requires a more concerted effort to raise awareness of and begin a discussion on CCD, including opportunities which might arise in trading Certified Emission Reductions from some European nations.

To summarize, the RINOVA study revealed that public perception of nuclear power are relatively inconsistent in Lithuania: despite public uncertainty about scientific knowledge, science is still regarded as the main actor taking responsibility for nuclear power issues. Just 44% of Lithuanian respondents think that society is responsible for nuclear energy issues, including safety and radioactive waste disposal, and that society should have a responsibility or legitimized power to participate in decision making. The support for new modern reactors is rather high, but they are still considered to have potential accident hazards. Positive symbolic meaning dominates public perceptions of NPPs in Lithuania, revealing economic and energy security concerns, on the one hand, and the radioactive waste disposal problem, on the other. Nuclear energy, including the radioactive waste disposal problem, was rated as a medium threat (3.52) by respondents asked to evaluate their perception of threats on a scale of 1 to 5. In Lithuania about 80% of the population agrees with the statement that there are safe ways of getting rid of high level radioactive waste.

CCD is almost unknown and there are no public debates on CCD in Lithuania. No risk perception studies have been conducted to date. The results of the recent EU project ACCSEPT indicated that the risk perceptions of CCD are greater in Lithuania and in other new EU member states than in the old EU countries (only 22 questionnaires were distributed in Lithuania, excluding parliamentarians, and the large majority of respondents were from the energy, research and government sectors). The survey demonstrated that Lithuanians were generally less enthusiastic about CCD than other nationals, and that Lithuanians perceived CCD to be less important in the national climate change debate. Lithuanians perceived the risks of CCD and the impacts upon decentralisation and energy security to be higher than citizens of old EU countries. New EU Member States, including Lithuania, require a more concerted effort to raise awareness of and begin a discussion on CCD.

7.3.3.3. Comparative analysis

Table 7.1 summarises the three case study findings regarding radioactive waste and CO_2 disposal in the three countries included in this study. It is based on the following items:

- Status of disposal technology categories: planned, research, development, operational;
- Risk assessment (‘objective’ risks): How high is the risk? Categories: low, medium, high;
- Public awareness of the technology: Self reported awareness based on polls, giving an indication of the presence of the issue in the general public (low, medium, high);
- Public knowledge: Do people know about disposal (three categories);
- Public opinion: Opinion is a verbalized attitude towards an issue (here final disposal) collected in polls, etc. Categories are ‘formed’ opinions or opinions in ‘formation’;
- Public debate: How intense is the debate and where does that debate take place? An indicator is the discourse in the media that can be intense, medium or low. National media and/or only regional and/or only local media were considered;

- Resistance: Is there resistance, at whatever stage these projects may be, from grassroots movements, national NGOs, political parties, etc.? Categories are low, medium, intense; the national, regional and local resistance movements were considered;

- Public participation: The category 'legal' means that the legally required formal procedures, regulations of spatial planning, etc. are applied in the licensing process. 'Participatory' means additional consensus building measures were applied at the national and/or regional/local level (e.g. round tables, public hearings).

7.4. CONCLUSIONS

There are some technical and institutional similarities between the disposal of CO_2 and radioactive waste in geological formations (e.g. all disposals have to separate the disposed material from the biosphere; a regulatory regime is necessary), but there are more differences [7.16], [7.21], [7.45]. To mention only a few: there is nothing like an interim storage for CO_2; radioactive waste poses a higher risk than CO_2 per unit of waste; monitoring (safety) and verification (safeguards) is important for radioactive waste disposals, whereas only safety is of relevance in the final disposal of CO_2. From the perspective of social acceptance, a crucial politically and socially virulent difference is that the negative opinions on nuclear energy and radioactive waste disposal are rather entrenched and stable in many countries, whereas the acceptance of CO_2 disposal is still in an early phase of development. Therefore, in many countries, nuclear energy and radioactive waste are connected with a web of negative and fearful symbols in the public mind [7.46], and radioactive waste disposal appears to be a wicked problem that is difficult to solve [7.47]. Even if risk perception of CCD in general is just developing and is still unstable, there is some evidence, based on findings of our case studies, that CCD will be considered less dangerous, and that these issues do not have the potential to create conflicts of comparable intensity to those in nuclear power that originates from entrenched long lasting antagonisms. Nevertheless, social acceptance is one challenge facing politics and society in both areas.

TABLE 7.1. COMPARATIVE ASSESSMENT

Country	Disposal Material	Status of technology	Risk assessment (‘objective’ risks)	Public awareness of the technology	Public knowledge on the technology	Public opinion	Public debate	Resistance	Public participation
Czech Republic	HLW	development	low	high	medium	formed	intense (local & regional) low (nationwide)	Intense (local & regional) medium (nationwide)	legal &participatory
	CO_2	research	low	low	low	limited, formation in the future	very general, formation in the future	low so far. medium can be expected	None for the moment
Germany	HLW	development	high	high	medium	formed	intense (nationwide)	intense (nationwide to local)	legal process, local information, round tables
	CO_2	research	low	low	low	process of formation	medium (local & regional)	intense (local to regional)	legal process, local information
Lithuania	HLW	research	high	high	low	formed	medium	no resistance	legal
	CO_2	research	low	low	low	formation	no debate	no resistance	legal

To cope with this challenge, information is required on the ‘objective risks’ in order to overcome knowledge deficits [7.48], even though knowledge is only one factor influencing risk perception, public opinion and attitude.

Another important task involves developing techniques for building a shared understanding of the issue [7.49] and developing strategies and ‘governance’ approaches to deal with complex risks [7.50]. To integrate people concerned from the very beginning in a participatory way is one strategy within these approaches, for example the “Facility Siting Credo” [7.51], [7.52], [7.53]. It could substantially contribute to public confidence in public decision making, if the Credo is properly implemented. The Swedish Nuclear Fuel and Waste Management Company has positive experiences with the early participation of the local population in selecting a site for radioactive waste disposal.

However, this credo and other general proposals for participation are facing criticism as sensible but abstract suggestions. The real challenge lies in implementing such approaches in a conflict ridden social environment [7.54]. Moreover, elements have been scrutinized. Studies on the benefit packages for individuals and/or host communities as ‘drivers’ of acceptance are inconclusive: some studies have found compensation to have a positive effect on siting acceptance, while others perceived compensation to be counterproductive [7.55], [7.56] because the rationale for resistance against projects is more varied than fears of property value losses that can be compensated.

Finally, there are good reasons to assume that people who could be affected by a disposal project on the ground would oppose that project, even if the ‘objective’ risk is low and the approval process is finished and legally sound. Opposition against a project appears ‘rational’ from the perspective of those affected. They bear the brunt of the risk, as small as it may be, and of other inconveniences (noise during drilling, injection, etc.), whereas the benefit (e.g. electricity from a low carbon source) is spread across the entire country. However, it is not always the people living closest to a planned project who oppose it most (NIMBY phenomenon). There are also findings that indicate the existence of an ‘inverse NIMBY’ phenomenon, i.e. that those who are closest support a project most (e.g. for wind energy projects [7.57] and cf. also the case studies presented in this chapter). In addition, media coverage sometimes gives the impression that most technological projects fail due to (local) resistance – in reality most projects are implemented without resistance and conflict. Therefore, acceptance research should not only concentrate on conflict, resistance and implementation failures, but also on successful projects and the conditions under which they were implemented smoothly.

There is no simple approach for coping with complex uncertain risks such as those associated with radioactive waste and CO_2 disposal [7.50] nor is there an institutional solution to the acceptance problem. Even participatory decision making is not the silver bullet for social acceptance [7.58]. It could be only one but important element in a complex regulatory process to make decisions and implement them, thereby taking into account national and local specifics. How difficult and discouraging this process could be and how challenging a new attempt might be is demonstrated by the debate about high level waste disposal in the USA [7.59], [7.60]. It is not a new, but a true message Todt has: “… more research is needed on the complex relationship between acceptance, trust, information and participation, the implications of non-standard methodology in regulatory decision making, as well as the different interpretations that stakeholders may give to key regulatory concepts.” [7.58]. An interesting field of research could be comparative case studies about *successful* siting processes. They could direct the (popular) viewer's scrutiny from failure to success and its conditions and frameworks.

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Chapter 8

POLICY, REGULATION AND INSTITUTIONS

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8.1. INTRODUCTION

Global climate change is currently a major challenge for humanity. Carbon dioxide (CO_2) is the dominant greenhouse gas (GHG), contributing more than 70% to the global GHG emissions. A major source of CO_2 emission is electricity production; it is responsible for nearly 40% of total CO_2 emissions [8.1]. This is primarily due to the overwhelming reliance by the electricity sector on fossil fuels, especially coal. For instance, currently coal accounts for approximately 30% of the world's electricity capacity and 40% of electricity generation [8.1].

In the absence of any significant transformation in the electricity technology fuel mix in the coming years, coal is expected to continue to occupy a central place in the electricity economy complex. For example, the share of coal based electricity is expected to increase to 44% by 2030, as the world contemplates an addition of nearly 4800 GW(e) capacity in order to meet an expected 76% growth in electricity demand over this period [8.2]. Further, by the year 2030, CO_2 emissions are expected to increase by 40%, with electricity contributing more than 60% to this increase [8.2].

Notwithstanding the uncertainties and discord that surround the global warming debate, there is a wide consensus on the enormity of the GHG challenge and hence the unsustainability of such high levels of CO_2 emissions from the electricity sector. The search is on for policy options to reduce CO_2 emissions. Two such options are nuclear power and fossil based power with the provision of carbon capture and disposal (CCD).

Considerable work has already been undertaken to analyse the cost effectiveness for electricity production from nuclear and coal fired power plants with CCD technologies. Much of this work has focused on the generation segments of the two industries, and to a lesser extent, on the transmission and distribution segments. Relatively little attention has been devoted to analysing the dynamics of radioactive waste and CO_2 disposal. Further, the general tenor of much of the existing analysis is techno-economic, focused on analysing technologies, technical potential and cost effectiveness. There is rather scant analysis of the policy, institutional and regulatory dimensions of radioactive waste and CO_2 disposal. This analysis is, however, critical because the extent to which technical potential will find policy/political acceptance will be largely determined by the efficacy of the policy, institutional and regulatory arrangements.

Against this backdrop, the main purpose of this chapter is to provide an overview of the policy, regulatory and institutional settings for CO_2 and radioactive waste disposal for selected countries, including Australia, the Czech Republic, Germany, the Republic of Korea, Lithuania and Switzerland. The policy settings, in the context of this chapter, refer to the political processes and governance paradigms. Regulatory settings focus on the prevailing rules for radioactive waste and CO_2 disposal. These rules can be in the form of acts, treaties, conventions, ordinances, agreements and regulations. Institutional settings are about institutional responsibilities, for example, for implementing radioactive waste and CO_2 disposal programmes, in accordance with prevalent rules.

This chapter is organized as follows. Section 8.2.1 presents a description of the key policy, regulatory and institutional aspects of radioactive waste storage and disposal for countries included in this study. Section 8.2.2 provides such a description for CO_2 disposal. Section 8.2.3 summarizes the key observations developed from a review of information in sections 8.2.1 and 8.2.2. Section 8.3 develops a comparative analysis of the policy, regulatory and institutional settings for various countries. Section 8.4 provides a summary of major findings of this chapter.

8.2. COUNTRY CASE STUDIES

8.2.1. Radioactive waste disposal

8.2.1.1. Policy

Uranium mining in **Australia** dates back to the 1930s. Australia is the largest supplier of uranium (for electricity production purposes) to the world, yet it does not have a nuclear power industry. However, it does have activities that use radioisotopes in medicine, research and industry. These activities generate low level wastes (LLW) and intermediate level wastes (ILW). These wastes are stored at several sites around Australia, but there is no dedicated national radioactive waste repository for long term disposal.

Nuclear power in Australia is a highly debated issue. There are sharply contrasting opinions on this issue amongst the political parties and the populace at large. Overall, the public sentiment in Australia is fiercely anti-nuclear. The government's proposal in 2007 to initiate a debate on this issue and to canvass support for the introduction of nuclear power was quickly abandoned due to public and political disquiet. Currently, the Australian government's policy for redressing the climate change challenge does not consider nuclear as an option – a testimony to the political sensitivity of this issue.

Australia is a federation of six states and two union territories. The Australian constitution accords differential powers to the federal and state governments. The states and territories have their own independent legislative powers for all matters not specifically assigned to the federal government. However, in matters of inconsistency between federal and state or territory laws, federal laws prevail [8.3].

The history of radioactive waste in the **Czech Republic** goes back to more than sixty years. The rapid expansion of nuclear energy in the 1960s and 1970s resulted in the accumulation of significant quantities of radioactive waste and the community was faced with the challenge of disposing of it. At that time, it was decided to dispose of low level radioactive waste in the near surface repositories, and of spent nuclear fuel and high level waste in underground rock formations [8.4].

Up to 40% of electricity in the Czech Republic is produced from nuclear power. The country has three research reactors, several radioactive waste storage facilities, a spent fuel interim storage facility and a low level radioactive waste repository [8.5]. It also has uranium ore mining and production facilities. A state owned company acts as the operator of all uranium production facilities.

The constitution of the Czech Republic gives the president considerable power, including the power to veto legislation. In 1993, the former Czechoslovakia was divided into the Slovak Republic and the Czech Republic [8.4]. To ensure a smooth and continuous transition, it was agreed that all acts, regulations and decisions in the field of nuclear energy and ionizing radiation would continue to apply until subsequent legislation was enacted [8.4]. Since then, multiple acts and regulations have been adopted by the Czech Republic to establish a comprehensive legal system in this field. The energy policy framework of the Czech Republic was adopted in 2004, set by the State Energy Policy. The basic priorities are to strive for independence from foreign energy sources, maximize the safety of energy sources, including nuclear power, and promote sustainable development [8.6].

Over the years, the management of spent fuel and high level radioactive waste has gained considerable public attention, primarily due to concerns about nuclear safety, especially after the Chernobyl accident [8.5]. The government therefore faces a major challenge in dealing with this perception and assuring the public of the effectiveness of its policies on radioactive waste disposal.

The political structure of **Germany** consists of a central Federal Government and 16 federal states (Länder). Radioactive waste disposal has traditionally been the responsibility of the Länder [8.7]. In 1959, the Atomic Energy Act was enacted, containing regulations about the safe use of radioactive substances. In the early 1960s and 1970s, this responsibility was carried out by the state owned nuclear research centres, but since 1976, it is a federal responsibility with the amendment of the Atom Law. Currently, the country has 17 nuclear reactors, located at 12 different locations. The responsibility for licensing the construction and operation of all nuclear facilities is shared between the federal and Länder governments. This arrangement effectively confers a power of veto to both levels of government [8.8]. The German nuclear industry is not directly responsible for the final disposal of radioactive waste, but the country's ‘polluter pays’ policy forces the industry to underwrite all of the costs for the preparation and disposal activities in proportion to its share in the resulting amount of waste [8.8].

In Germany, support for nuclear energy has been strong since the 1970s, following the oil price shock of 1974. However, in the aftermath of the Chernobyl accident in 1986, the Social Democratic Party (SPD) passed a resolution to abandon nuclear power within ten years. This created significant disagreements between the electric utilities and the government. In 2000, a compromise was reached between the Social Democrats/Green government and the utilities which prolonged the life of existing nuclear plants until about 2022 and prohibited the construction of new nuclear power plants (NPPs) and the reprocessing of spent fuel [8.8]. It also committed the existing utilities to store spent fuel on site.

In 2007, the International Energy Agency (IEA) warned that Germany's decision to phase out nuclear power would constrain its capacity to reduce carbon emissions. The agency therefore urged the government to reconsider this policy [8.8]. In 2009, following an election, a coalition government comprising Christian Democrat Union (CDU) and Liberal Democrat Party (FDP), was formed. In 2010, the government decided to extend the license for reactors built before 1980 by 8 years, and for those built after 1980 by 14 years. However, in 2011, after increasing pressure from anti-nuclear federal states and in the aftermath of the Fukushima accident, the government decided to phase out and close all reactors by 2022 [8.8].

Before the collapse of the Soviet Union, **Lithuania** had two large Russian reactors of the RBMK type. In 1991, Lithuania assumed the ownership of the Ignalina reactors. Lithuania stores its spent nuclear fuel in special containers within depots of ‘dry’ type, in the territory of the Ignalina NPP [8.9]. Lithuania also produces a small portion of waste by utilizing ionizing sources in medicine, research and industry. Initially, all radioactive waste generated was stored at two sites: the Ignalina NPP storage facilities and the Maišiagala disposal facility [8.10]. However, the Maišiagala Radon type waste storage facility has since closed.

Lithuania’s political system has undergone significant change over the last two decades. Following the country’s independence in 1991, a new constitution was introduced in 1992. The right to legislate belongs to the Seimas, the President of the Republic, the Government and 50 000 electors. The President may introduce draft laws, which the Seimas must debate. An issue of critical importance to the state or to the nation may be initiated by the Seimas. Such issues are generally initiated through referenda, or by the electorate, upon the presentation of 300 000 signatures [8.10]. In 1994, owing to external pressures and the Lithuanian interest in joining the European Union (EU), the country was required to shut down both nuclear reactors and to make its energy policy consistent with EU energy policy. Hence, unit 1 of Ignalina was closed in December 2004 and, despite strong public opposition to its enforced closure, unit 2 was closed at the end of 2009 [8.10]. The EU paid the decommissioning costs and provided other compensations from the Nuclear Safety Account administered by the European Bank for Reconstruction and Development (EBRD).

The progress in the harmonisation of the EU and the Lithuanian energy polices is monitored in terms of selected energy indicators of EU-15 countries. Lithuania is highly dependent on energy imports due to the unavailability of indigenous oil and natural gas resources and the rather high oil consumption rates. Thus, security of energy supply is an important policy issue for Lithuania. While the current Lithuanian primary energy supply mix is favourable with respect to greenhouse gas (GHG) emissions and the country’s commitment under the Kyoto Protocol [8.11], the imminent closure of the Ignalina NPP is likely to result in a higher share of fossil fuels, thereby impacting GHG emissions [8.12].

The **Republic of Korea** operates 21 nuclear reactors which meet 40% of the total electricity needs of the country. Plans are afoot for the expansion of the nuclear industry. For example, according to the Ministry of Education, Science and Technology's third comprehensive nuclear energy development plan for 2007–2011, the country proposes to increase the share of nuclear power to 60% by the year 2035 [8.13]. Such an expansion of nuclear industry is likely to pose significant challenges for the government in regards to the disposal of radioactive waste. The emerging public concerns about nuclear power, especially in the aftermath of the Fukushima accident, appear to have heightened the significance of this policy challenge. The energy policy in the Republic of Korea is heavily influenced by the considerations of energy security, especially the need to minimise import dependence. Nuclear power is an integral aspect of the country’s energy policy.

The legal basis for **Switzerland's** nuclear energy policy dates back to 1946, when the country’s Parliament approved the first resolution of the Federal Council concerning the promotion of nuclear energy [8.14]. In the 1960s, hydropower was one of the major sources of electricity in Switzerland. However, with increased demand for electricity it became evident that electricity utilities need alternative sources for producing electricity. The proposals to build coal and oil fired plants were strenuously opposed by the environmental groups. The government therefore encouraged the utilities to develop nuclear power. At present, Switzerland has five nuclear reactors generating 40% of its electricity needs and two other large units are planned [8.14].

Switzerland is a Confederation of 26 cantons (member states of the federation). The government, parliament and courts operate at three levels: federal, cantonal and communal. A notable aspect of Switzerland's political system is direct democracy, which allows an extraordinary amount of public participation in policy matters. Such participation has traditionally exerted a significant influence in the shaping of public policies in Switzerland. For example, in a referendum held in 2003, the public overwhelmingly rejected two anti-nuclear proposals, namely 'Electricity without Nuclear' and 'Moratorium Plus' [8.14]. The ongoing concerns about safety of nuclear have, however, resulted in the government decision not to replace any reactors, and hence to phase out nuclear power by 2034 [8.14].

8.2.1.2. Regulation and Institutions

Table 8.1 provides an overview of the key regulations (acts, conventions and treaties), their foci and implementing organizations [8.15], [8.16], [8.17], [8.18], [8.19]. Table 8.2 presents the key institutions and responsibilities. Details of state level regulations for radioactive waste disposal in Australia are presented in Table 8.3. Table 8.4 provides an overview of state level institutions for radioactive waste disposal in Australia.

8.2.2. Carbon dioxide disposal

8.2.2.1. Policy

The **Australian** economy is carbon intensive. It relies heavily on coal as a domestic fuel resource as well an export commodity. The Australian Government is committed to reducing its greenhouse gas (GHG) emissions by 60% of the 2000 levels by 2050. This will require a significant reduction in its CO_2 emissions from coal fired power stations and other coal based industries [8.20]. With fierce anti-nuclear sentiments at both political and public levels, the government faces an immense pressure to find suitable alternatives to meet its targets. Recently, the government announced its comprehensive plan to move towards a clean energy future [8.20]. In this plan, the government has proposed a suite of policy measures to reduce CO_2 emissions, including CO_2 disposal. The CCS Flagships Program and the National Low Emissions Coal Initiative (NLECI) to accelerate the deployment of large scale integrated carbon capture and disposal projects in Australia are integrated aspects of government's Clean Energy Initiative [8.20].

Australia has lately been active in CCD research, development and demonstration activities. For example, in the backdrop of the Gorgon Project, Australia has introduced the world's first legislation allowing for offshore geological disposal and has undertaken the world's first commercial release of offshore exploration areas for greenhouse gas disposal assessment [8.20]. Furthermore, government has established the Global Carbon Capture and Storage Institute (GCCSI) to accelerate the global deployment of CCD technology. There has been significant bipartisan support for CCD and the present government believes that Australia can maintain its strong economic position and continue to grow by getting clean energy at the lowest possible costs.

TABLE 8.1. RADIOACTIVE WASTE: REGULATION, OBJECTIVES, ORGANIZATIONS

		ACTS, CONVENTIONS,TREATIES	OBJECTIVE	ORGANIZATIONS
Australia	International	The London Dumping Convention Act No.16 of 1985	-Prevent dumping of radioactive waste at sea	DFAT
		South Pacific Nuclear Free Zone (Treaty of Rarotonga) Act No.140 of 1986	-Bans manufacture, possession, stationing and testing of any nuclear explosive device in Treaty territories and dumping of radioactive waste at sea	DFAT
		Nuclear Non-Proliferation (Safeguards) Act No.8 of 1987	-Foster peaceful use of nuclear energy; achieve complete disarmament and regulates possession, transport and communication of nuclear material	IAEA (central role), DFAT
		Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	-Promotes the safe management of spent fuel and radioactive waste in terms of storage, transport, treatment and disposal	IAEA (central role), ANSTO
	Commonwealth	ANSTO Act Act No.3 of 1987	-Conduct R&D in nuclear technology, manage radioactive waste, provide advice to government in nuclear activities	Department of Innovation, Industry, Science and Research, ANSTO
		ARPANS Act Act No.133 of 1998	-Regulate nuclear installations and radiation management in terms of safety and health	Department of Health and Ageing, ARPANSA
		EPBC Act Act No.91 of 1999	-Protect internationally important flora, fauna, ecological communities and heritage places, which are matters of national environmental significance	Department of Sustainability, Environment, Water, Population and Communities
		The Commonwealth Radioactive Waste Management Act Act No.145 of 2005	-Develop and operates proposed Commonwealth radioactive waste management facility in Northern Territory	DRET
		Lands Acquisition Act 1989	-Ensure that Commonwealth does not make compulsory land acquisition of land unless State or Territory Government in which the land is situated has consented	Department of Finance and Deregulation
Czech Republic	International	Vienna Convention on Civil Liability for Nuclear Damage	-Ensure that justice was available for victims outside of the country in which an accident occurs so far as countries that are party to relevant conventions	IAEA, SÚJB
		Nuclear Non-Proliferation (Safeguards)	-Foster peaceful use of nuclear energy; achieve complete disarmament and regulates possession, transport and communication of nuclear material	IAEA, SÚJB
		Convention on the Physical Protection of Nuclear Material (1979)	-Provides physical protection during international transport of nuclear material; Establish framework for cooperation among states in protection, recovery, and return of stolen nuclear material	IAEA, SÚJB
	National	The Atomic Act (Act No. 18/1997)	-Regulate activities involving nuclear energy and ionising radiation and to protect public and environment against their harmful effects	SÚJB
		EIA (Act No. 244/1992)	-Regulates in accordance with EC laws; Assess impact on public health and environment	Ministry of Environment

TABLE 8.1. NUCLEAR WASTE: REGULATION, OBJECTIVES, ORGANIZATIONS (CONT.)

Czech Republic	National	Regulations introduced	-Regulation Min. of Health No 59/1972- General Principles of the Law on Protection Against Ionizing Radiation; No. 195/1999 Coll., on Basic Design Criteria for Nuclear Installations with Respect to Nuclear Safety Radiation Protection and Emergency Preparedness; No. 196/1999 Coll., on Decommissioning of Nuclear Installations and Working Places with Important and Very Important Sources of Ionizing Radiation; No. 324/1999 Coll., on Limits of Concentration and Amount of Nuclear Material for which Nuclear Liability Requirements do not Apply; Transport of Nuclear Materials	Ministry of Health, SÚJB
		Concept of Radioactive Waste and Spent Nuclear Fuel Management (2002)	-Site selection strategy for future deep repository based ecological investigation work and must be beneficial for communities concerned	IAEA, SÚJB RAWRA
Germany	International	Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	-Promotes the safe management of spent fuel and radioactive waste in terms of storage, transport, treatment and disposal	BMU
		Convention on Nuclear Safety	-Aims to legally commit participating States operating nuclear power plants to maintain a high level of safety by setting international benchmarks to which States would subscribe	IAEA, BfS
	National	Atomic Energy Act	-Radioactive waste must be properly disposed based on the waste characteristics and must be placed in interim storage facilities until disposal	BMU
		Radiation Protection Ordinance	-Regulate activities involving nuclear energy and ionising radiation and to protect public and environment against their harmful effects	BMU
		Environmental Impact Assessment Act	-Regulate environment assessment activities; Public and environment authorities may give their opinion on projects likely to have impact on environment	BMU
Lithuania	International	Vienna Convention of Civil on Civil Liability for Nuclear Damage of 1963	-Ensure that justice was available for victims outside of the country in which an accident occurs so far as countries that are party to relevant conventions	IAEA, Ministry of Economy
		NPT of 1968	-Foster peaceful use of nuclear energy; achieve complete disarmament and regulates possession, transport and communication of nuclear material	IAEA, Ministry of Economy
		CTBT of 1996	-Bans all nuclear weapon test explosion or any other nuclear explosion, achieve complete disarmament and prevent further nuclear weapon modernization and subsequent arms races	Ministry of Economy
	National	Law on Nuclear Energy (1996)	-Radioactive waste may be disposed in conformity with procedures prescribed by laws and regulations of Republic of Lithuania	VATESI
		Law on Radiation Protection (1999)	-Regulates activities involving sources of ionising radiation and radioactive waste management	VATESI
		Law on Management of Radioactive Waste (1999)	-Ensure that at all stages of radioactive waste management protects individuals, society and the environment in Lithuania against hazards associated with radioactive waste	VATESI

TABLE 8.1. NUCLEAR WASTE: REGULATION, OBJECTIVES, ORGANIZATIONS (CONT.)

Lithuania	National	Law on Earth Entrails (1995)	-States that earth entrails is property of the state and regulates exploration and usage of earth entrails including issue of permits and licences	Ministry of Environment
		Law on Environmental Impact Assessment (1996)	-The site of a radioactive waste management facility shall be made pursuant to requirements of Law on Territorial Planning and Law on the Environmental Impact Assessment of Planned Economic Activity	Ministry of Environment
		Strategy of Radioactive Waste Management (2002)	-Must be updated by government by taking principal decisions about construction and exploitation of disposal sites, preparing relevant legal framework for waste management	Ministry of Economy
Republic of Korea	International and National	NPT of 1968	- Foster peaceful use of nuclear energy; achieve complete disarmament and regulates possession, transport and communication of nuclear material	IAEA, MKE
		AEA	-Provides for basic and fundamental matters concerning nuclear safety regulations	MKE
		Enforcement Decree of the AEA Regulations	-Provides technical standards and particulars entrusted by AEA and necessary for enforcement of AEA	MKE
		Notice of the MOST	-Enforcement Regulation of AEA; Enforcement Regulation Concerning the Technical Standards of Reactor Facilities, etc.; Enforcement Regulation Concerning the Technical Standard of Radiation Safety Management, etc.	MOST
		The Radioactive Waste Management Act	-Notice provides the detailed particulars for technical standards and guidelines; It integrates and systematically determines all aspects of managing radioactive waste	MOST, KRMC
Switzerland	International	NPT of 1968	- Foster peaceful use of nuclear energy; achieve complete disarmament and regulates possession, transport and communication of nuclear material	IAEA, Federal Council
		Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	-Promotes the safe management of spent fuel and radioactive waste in terms of storage, transport, treatment and disposal	IAEA, Federal Council
	National	Federal Atomic Energy Act of 1959	-Dealt with radioactive waste only from the viewpoint of license, revocation of license for its possession and transport of radioactive substances; Amendments included obligation of waste producer to organise its safe disposal; Waste produces is obliged to cover the costs of waste disposal	Federal Council, OFEN
		Transport Ordinances	- Transport by rail is regulated by Transport Regulations, Air transportation of dangerous goods is regulated by the IATA; Federal Council on transport of dangerous goods provides that foreign vehicles not meeting norms of Switzerland are not allowed in	DETEC
		Act on Nuclear Third Party Liability (LRCN), 1983	-Provides that person liable must commit for an unlimited amount	Federal Council

TABLE 8.1. NUCLEAR WASTE: REGULATION, OBJECTIVES, ORGANIZATIONS (CONT.)

Switzerland	National	Ordinance on construction of repositories, 1989	-Federal Council must grant a license before preparatory measures can be undertaken for the safe construction of radioactive waste repositories	Federal Council DETEC
		Radiological Protection Ordinance, 1994	-Waste producers must make provision for the temporary storage of waste at the site of production and submit details of their proposal for approval	OFSP
		Ordinance on the Nuclear Waste Collection, 1994	-Collection of waste must be organised and sent to the collection centres designated by the public authority, either to be stored in repository or to be disposed	OFSP
		Nuclear Energy Ordinance, 2005	-Federal State takes over the responsibility for collection, conditioning, storage and disposal of radioactive waste generated by use of radioisotopes in medicine, industry and research -Radioactive waste shall be disposed of in geologic repositories; the eventual closure of a repository is preceded by an observation phase until closure of the repository	DETEC, OFEN, HSK

TABLE 8.2. RADIOACTIVE WASTE: KEY INSTITUTIONS AND RESPONSIBILITIES

	ORGANISATIONS	RESPONSIBILITIES
Australia	ANSTO	-R&D in nuclear science and technology
	ARPANSA	-Promote radiation protection and nuclear safety policy and practices across Australian jurisdictions; Undertake research in radiation protection and provide services; Ensure nuclear safety and medical exposure to radiations; Regulate entities using radioactive substances and nuclear technology
	DFAT	-Administer International Acts, Conventions and Treaties on nuclear material and technology
	DRET	-Approve permits nuclear material export
	Department of Sustainability, Environment, Water, Population and Communities	-Assess and approve nuclear actions as with potential impact on environment
	Department of Health and Ageing	-Administers functioning of ARPANSA[8.15]
	Department of Innovation, Industry, Science and Research	-Policy direction for ANSTO to undertake R&D in nuclear technology[8.15]
	Department of Finance and Deregulation	-Provide monetary assistance to ANSTO

TABLE 8.2. RADIOACTIVE WASTE: KEY INSTITUTIONS AND RESPONSIBILITIES (CONT.)

Czech Republic	SÚJB	-Supervises nuclear safety, radiation protection and emergency preparedness of nuclear installation and management of radioactive waste (OECD 2003b)
	RAWRA	-Ensure safe disposal for radioactive waste, monitor and supervise repositories after their closure
	CEZ	-Electricity generation and implementing regulatory decisions
	Ministry of the Environment	-Regulate nuclear activities to ensure that they comply with environmental laws[8.5]
	Ministry of Health	-Protect people and environment against harmful effects of radiation
Germany	BMU	-Responsible for licensing and supervising activities of nuclear facilities with respect to Federal States
	BfS	-Construct and operate nuclear waste facilities [8.16]
Lithuania	VATESI	-Regulate nuclear safety and radiation protection at nuclear power and waste management facilities(ENSERG 2011a)
	Ministry of Environment and Ministry of Health	-Regulates radiation released to environment and creates environmental regulations for future radioactive waste management facilities (ENSERG 2011a)
	RATA	-Responsible for management and final disposal of radioactive waste generated by the Ignalina NPP .RATA's activity are administered by VATESI and Radiation Protection Centre [8.17]
	Ministry of Energy	-Responsible for coordinating activities of Radioactive Waste Management Agency
Republic of Korea	MKE	-Supervise nuclear power program and manages radioactive waste treatment, storage, and disposal
	MOE	-Regulate environment issues except radiological environment
	MOST	-Nuclear safety regulations including licensing; Develop standards for safety measures at every stage of site selection, design, construction, operation, closure, and post-closure of radioactive waste disposal facilities[8.18]
	KRMC	-Manage radioactive waste management fund
Switzerland	Federal Council	-Develop nuclear legislation and license and supervise nuclear installations[8.19]
	DETEC	-Construct and operate nuclear facilities; Part of DETEC, responsible for preparing and applying legislation in field of nuclear energy
	OFEN	-Operates with Federal Department of Foreign Affairs on implementing international nuclear treaties
	HSK	-Supervise nuclear facilities under administration of OFEN; Specify safety requirements and reviews license applications [8.14]
	OFSP	-Supervise radiation protection

TABLE 8.3. STATE LEVEL REGULATIONS FOR RADIOACTIVE WASTE DISPOSAL ACTIVITIES IN AUSTRALIA

REGULATION	OBJECTIVES	ADMINISTRATION
NSW Radiation Control Regulation SL.No.615 of 2003	- Deals with licensing, registration, accreditation and approvals of radioactive substances - Regulates the use, disposal, transport and discharge of radioactive substances	Office of Environment and Heritage within NSW Department of Premier and Cabinet
VIC Radiation Act Act No.62 of 2005	- Protect the health and safety of people and the environment from the harmful effects of radiation - Regulate the practice of radiation sources in medical, industrial, research, and mining sectors	Department of Health
VIC Radiation Regulation SL.No.89 of 2007	- Prescribe activity concentration of the emission, radiation dose limits, and radiation sources that require certificate of compliance prior to use of the source	Department of Health
QLD Radiation Safety Act Act No.20 of 1999	- Protect people and environment from the harmful effects of ionising and non-ionising radiation	Queensland Health
QLD Radiation Safety Regulation 2010 Repeals Radiation Safety Regulation 1999, SL. No. 330	- Deals with ionising and non-ionising radioactive emission, transport, disposal, radiation monitoring, dose limits, radiation safety and protection plans	Queensland Health
SA Radiation Protection and Control Act Act No.49 of 1982	- Deals with human health risks arising from exposure to radiation, which should be kept reasonably low	EPA Government of SA
SA Radiation Protection and Control (Ionising Radiation) Regulations 2000	- Regulates the ionising radiation apparatus in terms of licensing, registration, storage, disposal and sale of radioactive substances - Deals with radiation protection standards and limits, monitoring, reporting incidents and accidents, and conducting medical examinations of employees	EPA Government of SA
SA Radiation Protection and Control (Transport of Radioactive Substances) Regulations 2003	- Prescribes the responsibilities of Consignor, Carrier, Driver and Storekeeper as per the Code of practice for the safe transport of radioactive substances	EPA Government of SA
SA Radiation Protection and Control (Non-Ionising Radiation) Regulations 2008	- Deals with licensing of non-ionising radiation apparatus	EPA Government of SA
SA Nuclear Waste Storage Facility (Prohibition) Act 2000	- Aimed at banning the construction of nuclear waste management facilities in SA, with an exception of facilities to manage low level waste	EPA Government of SA

TABLE 8.3. STATE LEVEL REGULATIONS FOR RADIOACTIVE WASTE DISPOSAL ACTIVITIES IN AUSTRALIA (CONT.)

TAS Radiation Control Act Act No.66 of 1977	- Regulates the use of radioactive materials and electronic products producing radiation	Department of Health and Human Services
TAS Radiation Control Regulations SL.No.237 of 1994	- Regulates the storage, transport and disposal of radioactive substances	Department of Health and Human Services
TAS Radiation Protection Act Act No.48 of 2005	- Ensure the safety of people and protection of environment from the harmful effects of radiation	Department of Health and Human Services
TAS Radiation Protection Regulations SL.NO.37 of 2006	- Deals with licensing, registration, accreditation and issue of Certificates of Compliance - Regulates the radiation management plan, storage, transport and disposal of radioactive substances	Department of Health and Human Services
ACT Radiation Protection Act Act No.33 of 2006	- Protect the health and safety of people, property and the environment from the harmful effects of radiation	Radiation Safety of ACT Health Services
NT Radiation (Safety Control) Act Repealed by Radiation Protection Act 2004	- Dealt with the control, regulation, possession, use and transport of radioactive substances and irradiating apparatus	Department of Health
NT Radiation Protection Act Act No.23 of 2004	- Protect people and environment from the harmful effects of radiations	Department of Health
NT Radiation Protection Regulations SL.No.20 of 2007	- Deals with licensing, registration, accreditation and approval of radiation protection plan - Provide information on infringement offences and notices	Department of Health
WA Radiation Safety Act Act No.44 of 1975	- Regulates the use of both ionising and non-ionising radioactive substances and electronic products	Department of Health, Radiological Council(Statutory Body)
WA Radiation Safety (General) Regulations 1983	- Prescribes general precautions and requirements related to safety of radioactive substances, irradiating apparatus and electronic products	Department of Health, Radiological Council(Statutory Body)
WA Radiation Safety (Qualifications) Regulations 1980	- Deals with qualification and syllabus for examination of person engaged in radiation safety	Department of Health, Radiological Council(Statutory Body)
Nuclear Waste Storage Facility (Prohibition) Act 1999	- Protects the health, safety and welfare of people and the environment of WA by prohibiting the establishment of nuclear waste storage facility in the state	Department of Health, Radiological Council(Statutory Body)
WA Radiation Safety (Transport of Radioactive Substances) Regulations 2002	- Prescribes the responsibilities and offences for the transport of radioactive substances as per the Code and International Regulations	Department of Health, Radiological Council(Statutory Body)

TABLE 8.4. STATE LEVEL INSTITUTIONS FOR RADIOACTIVE WASTE DISPOSAL ACTIVITIES IN AUSTRALIA

ORGANISATION	RESPONSIBILITY
NSW Department of Premier and Cabinet OEH	- Regulates use of radioactive substances and radiation equipment in NSW - For matters of environment protection, OEH acts under the powers of statutory EPA
Department of Health Victoria	- Promotes radiation safety procedures and practices - Recommends criteria for licensing to use radiation sources - Recommends radiation safety standards, codes of practice, standards for radiation sources, practices or uses
Queensland Health Radiation Health Unit is the QLD government's radiation safety agency	- Deals with policy, licensing and legislative responsibility for radiation health standards and radiation safety; - Administers the Radiation Safety Act and Regulation which regulates sources of ionising radiation
EPA Government of South Australia	- EPA is the environmental regulator of SA - Administer the Radiation Protection and Control Act 1982, as well as the development of guidelines and codes of practice for the same
Department of Health and Human Services of Tasmania	- Radiation Protection Unit regulates the use of radioactive materials in Tasmania
ACT Health Services	- Develops radiation protection policy and advice to the community
Radiation Safety of the Health Protection Service of ACT	- Deals with licences and registrations for radiation sources - Supervises radiation waste disposal
Department of Health of Northern Territory	- Radiation Protection is a work unit within the Environmental Health Program - Deals with the legislation that authorises the sale, acquisition, possession, use, storage, transport and disposal of radioactive materials and apparatus
Department of Health of Western Australia	- Radiological Council is an independent statutory body appointed under Radiation Safety Act to assist the Minister for Health to protect health and maintain safe practices in use of radiation

Notes to Tables: ACT=Australian Capital Territory; AEA=Atomic Energy Act; ANSTO=Australian Nuclear Science and Technology Organization Act; ARPANSA=Australian Radiation Protection and Nuclear Safety Act; BfS=Federal Office for Radiation Protection; BMU= Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; BMWi=Federal Ministry of Economics and Technology; CEZ=Ceske Energetic Saved; DETEC=Federal Department for Environment, Transportation, Energy and Communication; DFAT=Department of Foreign Affairs and Trade; DRET=Department of Resources, Energy and Tourism; EC=European Communities; EPA= Environmental Protection Agency; EPBC=Environment Protection and Biodiversity Conversation; FOEN=Swiss Federal Office for the Environment; GCCSI=Global Carbon Capture and Storage Institute; HSK=Swiss Federal Nuclear Safety Inspectorate; IATA=International Air Transport Association; KRMC=Korea Radioactive Waste Management Corporation; MCMPR= Ministerial Council on Mineral and Petroleum Resources; MKE=Ministry of Knowledge Economy; MOE=Ministry of Environment; MOST=Ministry of Education, Science and Technology; NSW=New South Wales; NT=Northern Territory; OEH=Office of Environment and Heritage; OFEN=Federal Energy Office; OFSP=Federal Office of Public Health; QLD=Queensland; RATA= Lithuanian Radioactive Waste Management Agency; RAWRA= Radioactive Waste Repository Authority; SA=South Australia; SFOE=Swiss Federal Office of Energy; SUJB=State Office for Nuclear Safety; TAS=Tasmania; VATESI= State Nuclear Power Safety Inspectorate; VIC=Victoria; WA=Western Australia

The **Czech Republic** is committed to reducing its greenhouse gases (GHG) under the Kyoto Protocol by 8% of the 1990 levels by 2012. The country's GHG emissions have already reduced considerably over the past few years, yet its per capita emissions are higher than the EU average and much higher than the global average. The country is therefore currently preparing a Climate Protection Policy that will include measures to further reduce GHG emissions.

As a Member State of the European Council, the Czech Republic has an obligation under the EU Law to transpose the provisions of Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the Geological Storage of Carbon Dioxide and Amending Council Directive (known as the EU CCS Directive) into national law and to communicate the text of any such laws and other administrative measures to the European Commission [8.21]. The Czech Republic has, however, failed to comply with these requirements.

Regardless, several measures have been taken at the national level to develop a comprehensive CCD legal and regulatory framework. For example, the Ministry of Environment submitted a draft of CCS Law for approval by the government on 14 March 2011. The government's Legal Council, however, sent the draft law back to the Ministry for revision [8.22]. After long discussions, the law was finally accepted in February 2012 as the Act No. 85/2012 Coll. on CO_2 disposal into geological structures and about the change of some of the laws.

The climate change debate in **Germany** has its origins in the controversy over nuclear power triggered by the 1986 Chernobyl nuclear accident. With calls for an immediate shutdown (mainly by the Greens) or phase-out (particularly by the SPD) of all nuclear plants, the construction of additional coal fuelled power plants was proposed to compensate for the lost capacity of nuclear facilities [8.8]. Carbon capture and disposal (CCD) is one of the pillars of the European climate change efforts [8.21]. As the technology is new, the necessary legal framework is still developing. Germany does not yet have a specific legal regime for CCD, but is in the process of implementing the European CCS Directive 2009/31/EC on the geological disposal of carbon dioxide. Germany began working on its CCS Law in 2008 and the first draft was approved by the Cabinet in April 2009. However, owing to public opposition and approaching federal election, no progress was made on the draft in the following years. In July 2011, the Bundestag (German Parliament) approved one billion Euros for the CCS Act that regulates demonstration projects. The Bundesrat, the legal body that represents the German federal states, which has to consent, however, refused (in September 2011) to consent with this proposal. The law therefore failed, and German CCD policy has since then been in a state of deadlock [8.22]. A small pilot program for CCD currently exists in Ketzin is coordinated by the GFZ German Research Centre for Geosciences [8.22] – see Chapter 7.

Germany is currently the largest emitter of GHGs in Europe and, like other member states of the European Union, it is required to meet its Kyoto targets for GHG emissions. Germany has committed itself, under the Burden Sharing Agreement, to reduce GHG emissions by 21% of the 1990 levels over the period 2008–2012 [8.11]. Germany also has a self imposed mid term goal of cutting its emissions by 40% of the 1990 levels by 2020 and simultaneously phasing out nuclear energy by 2022.

The main goals of the **Lithuanian** energy policy, as set out in the Law on Energy, are: energy conservation, efficient consumption of primary energy resources, stimulation of producers and consumers to efficiently use and consume indigenous, renewable and waste energy resources, and reduction of hazardous environmental impact by the energy sector. This law also requires that the national tax policy, soft loans or subsidies provided by the state (municipality) must stimulate efficient energy use and consumption of renewable and waste energy resources [8.11].

Lithuania is currently facing two major challenges in the energy sector, namely, the closure of the Ignalina NPP (in 2009) and the Maišiagala radioactive waste disposal facilities (in 2010) on the one hand, and meeting its GHG mitigation targets under the Kyoto Protocol on the other. The country decided to evaluate different options for reducing CO_2 emissions, including an assessment of geological CO_2 disposal potential and construction of a new nuclear power plant [8.10]. Lithuania is one of the 12 Member States that adopted the EU CCS law. This law will regulate the underground disposal of CO_2. The CCS Directive lays down requirements for the lifetime of a CO_2 disposal site and also covers measures for dealing with CO_2 leakage, the need for disposal site permits and the responsibility for disposal sites once they are closed [8.21], [8.22].

The **Republic of Korea** ratified the Kyoto Protocol in 2005, but owing to its industrial structure and limited policy options, the Republic of Korea's GHG emissions in 2010 were higher than other major developing economies like China and India. The energy policy for the country envisaged more than a 10% reduction of total energy consumption and an approximate 5% contribution from renewable sources by 2011.

The Republic of Korea has actively participated in the GHG mitigation activities through the Kyoto mechanisms like the Clean Development Mechanism (CDM). The Republic of Korea's Emissions Trading Scheme (ETS) was planned to be launched in 2013 but it was delayed due to opposition from the country's industrial sector [8.11]. Now, emissions trading is proposed to be launched sometime between 2014 and 2015. The government aims to reduce greenhouse gas emissions by 30% from the projected levels by 2020. Other policies likely to be considered in the future include carbon tax and smart grid, but the plans are still in the review stages and the time frame for their implementation has not yet been decided.

In January 2009, in a meeting jointly held by the National Science Technology Committee and the Future Planning Committee and hosted by the President of the Republic of Korea, the Korean government announced a Vision and Development Strategy for a new government policy related to CCD called 'New Growth Engine' [8.23]. Three New Growth Engine sectors and 17 New Growth Engine industries were also designated and announced. The three New Growth Engine sectors are green technology industry, high tech fusion industry and high value added service industry. CCD and other CO_2 related policies fall under the category of green technology industry [8.23]. The purpose of the New Growth Engine is to expand the growth potential of the Korean economy through the joint efforts of the public and private sectors. The policy initiatives are expected to have durations in the range of three to ten years; specific projects involve research and development, tax benefits, system improvement and human resource development [8.23].

Switzerland is an early signatory to the Kyoto Protocol. In 2005, the Swiss Federal Council declared that the obligation of Switzerland under the Kyoto Protocol (i.e. 8% reduction in GHG emissions by 2008–2012, relative to 1990) has to be met by a combination of targeted policy measures [8.11]. In 1999, the Swiss parliament passed the CO_2 Act as the centrepiece of its climate policy [8.24].

The energy articles in the Swiss Federal Constitution, the Energy Act, the CO_2 Act, the Nuclear Energy Act and the Electricity Supply Act are all integral parts of the instruments for defining a sustainable and modern energy policy. In addition to these legal instruments, the energy policies of the federal government and the cantons are also influenced by energy perspectives and strategies, implementation programmes and a careful evaluation of energy related measures at the municipal, cantonal and federal levels.

The two main planks of Swiss energy policy are to promote the use of renewable resources and to encourage efficiency [8.22]. Switzerland does not see immediate potential for CCD. However, to cope with a potential energy supply gap by 2020, it has planned to build combined cycle gas turbine plants and such plants are required to fully compensate for their CO_2 emissions, making associated CCD deployment a potential solution [8.25], [8.26]. Research projects have also begun in Switzerland for assessing the feasibility of deploying CCD. Two studies conducted within the CARMA research project focus on the knowledge and public perception of CCD among Swiss laymen [8.22]. So far, though, the government has not taken any initiative in developing guidelines for CCD.

8.2.2.2. Regulation and institutions

Table 8.5 provides an overview of the key regulations (acts, conventions and treaties), their foci and implementing organizations. Table 8.6 presents the key institutions and responsibilities.

8.2.3. Country specific conclusions

Radioactive waste disposal

Australia has a generally well defined policy on the disposal of LLW and ILW radioactive waste. This policy is, however, largely disconnected from its overall electricity policy settings because Australia does not have a nuclear power industry. Further, the constitutional arrangements on resource matters and the adversarial nature of Commonwealth and state relations in Australia are likely to militate against the development and adoption of a unified ‘national’ policy on radioactive waste disposal should Australia decide to develop its own nuclear power industry, or agree to act as a repository of radioactive waste from other countries.

The institutional arrangements for implementing nuclear regulation, including radioactive waste disposal, are rather complex. For example, ANSTO is responsible for implementing radioactive waste acts, and ARPANSA for regulating the acts. ARPANSA is also responsible for issuing licenses to ANSTO to operate its facilities; it also undertakes a range of investigations [8.27]. This arrangement suggests that these two organizations, although apparently independent, are in fact strongly interdependent. This has raised issues in the past. For instance, owing to the communication gap between ARPANSA and ANSTO, there have been instances of repeated license breaches by ANSTO [8.28].

TABLE 8.5. CO_2 DISPOSAL: REGULATION, OBJECTIVES, ORGANIZATIONS

ACTS, CONVENTIONS AND REGULATIONS	OBJECTIVE	ORGANIZATIONS
	AUSTRALIA	
The London Dumping Convention	-Prevents dumping of waste in sea; Amendment in 2006, to allow offshore CO_2 storage; Amendment in 2009, to allow cross-border transportation for the purpose of CO_2 storage	DFAT
Regulatory Guiding Principles for Carbon Capture and Storage 2005	-Designed to achieve a consistent regulatory framework for all CCS activities in Australian jurisdiction, key issues identified are: assessment and approvals processes; access and property rights; transportation issues; monitoring and verification; liability and post-closure responsibilities and financial issues [8.25]	MCMPR
Offshore Petroleum and GGS Act	-Deals with petroleum exploration and recovery, and the injection and storage of greenhouse gas substances, in offshore areas	DRET
EPBC Act	-Protects internationally important flora, fauna, ecological communities and heritage places, which are matters of national environmental significance	Department of Sustainability, Environment, Water, Population and Communities
	CZECH REPUBLIC	
EU CCS Directive	-Implement EU legislation on geological storage of CO_2[8.26]	Ministry of Environment; Ministry of Industry and Trade
	GERMANY	
EU CCS Directive	-Implement EU legislation on geological storage of CO_2	BMU, BMWi
CCS Act -Zustimmungsgesetz ("consent law")	- To allow demonstration projects in Germany; Includes provision for application for demonstration projects, storage capacities of the sites and the government shall report to the Budestag by 31st December 2017 on the experience gained by the demonstration projects.. Owing to the rejection of that by the Bundesrat, Germany is without a CCS law and the EU Commission may take legal action against Germany [8.22]	BMU, BMWi
Mining Law	-For the purpose of CO_2 storage Mining law may apply where CO_2 storage shall take place in the context of oil and gas production or using brine caverns	BMU, BMWi
	LITHUNIA	
EU CCS Directive	-Implement EU legislation on geological storage of CO_2 [8.26] -At present there are no laws regulating CO_2 storage	Ministry of Environment; Ministry of Energy
	REPUBLIC OF KOREA	
Atmospheric Environment Preservation Law	-Regulates the emission of air pollutants; Prescribes the permissible levels of emissions of air pollutants [8.23]	MKE
Hazardous Substance Safety Management Law	-Provides the framework of rights and obligations which could govern the storage, installation of storage facilities, and pre-closure management in relation to CCS projects [8.23]	MKE
Mining Law	-Regulates mining exploration plans and conditions for mining licences, administered by MKE [8.23]	MKE

TABLE 8.5. CO_2 DISPOSAL: REGULATION, OBJECTIVES, ORGANIZATIONS (CONT.)

	SWITZERLAND	
Swiss CO2 Act	- Specifies 10 % less CO_2 by 2010 as a reduction target; Measures include voluntary reduction by industries and individuals, CO_2 tax, emissions trading, improve energy efficiency and use renewable energy and others [8.24]	FOEN; SFOE

TABLE 8.6. CO_2 DISPOSALS: KEY INSTITUTIONS and RESPONSIBILITIES

ORGANISATIONS	RESPONSIBILITIES
	AUSTRALIA
DRET	-Supports CCS research, both pilot and commercial scale demonstration projects and is managing the development of offshore CO_2 storage resources
MCMPR	-Consists of the Commonwealth Minister for Resources, Energy and Tourism and State and Territory Ministers with responsibility for minerals and petroleum; Released the Regulatory Guiding Principles to achieve a consistent approach in implementation of CCS scheme
Department of Sustainability, Environment, Water, Population and Communities	-Develop and implement national policies, programs and legislations to protect and conserve the natural environment, promote and support ecologically sustainable development
GCCSI	- Accelerate the deployment of CCS technology globally through: sharing knowledge; fact-based advocacy and assisting projects
	CZECH REPUBLIC
Ministry of Environment	-Develop CCS legislation and regulate reforms in Czech Republic
Ministry of Industry and Trade	-Co-sponsor of CCS laws in Czech Republic and assist Ministry of Environment
	GERMANY
BMU, BMWi	-Both share responsibility to draft/formulate CCS law
State level	- Federal States (Länders) have responsibilities for issues related to CCS and land use and granting of permits [8.22]
	LITHUANIA
Ministry of Economy	- At present there are no laws regulating CO_2 storage
Ministry of Environment; Ministry of Energy	-Concerned institutions for managing environment and waste management laws [8.22]
	REPUBLIC OF KOREA
MKE	-Currently involved with creating a draft Basic Law on Low Carbon Green Growth which would provide a broad framework for sustainability policies in Korea [8.22]
	SWITZERLAND
FOEN	-Responsible for CO_2 Act
SFOE	-Coordinates with FOEN on CO_2 Act. Both the units are a part of the DETEC [8.22]

The regulatory arrangements for various stages of radioactive waste disposal are well defined, although their implementations (i.e. institutional arrangements) appear to be typified by overlaps. Another noteworthy feature of the regulatory arrangement is that there is a strong connect between the Australian and international regulatory regimes.

In the **Czech Republic** the state policy for radioactive waste disposal is based on the Atomic Act (Act No. 18/1997 Coll.) that defines the principles of radioactive waste management and disposal in the Czech Republic. The main principle is to dispose of low level waste and to store high level waste until final disposal, even though the reprocessing of the fuel might be possible in the future [8.29].

The lack of coherence in policy making has resulted in a 'policy capture'. For example, for the construction of a deep geological repository for the direct disposal of spent fuel and other high level waste in the Czech Republic, six sites were selected in 2005 on the basis of the 'Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic'. However, many communities protested against these developments and demanded, among other things, the strengthening of their role in the siting process, including the right of veto [8.30].

The licensing, nuclear safety, waste management, safeguards and radiation protection are regulated by the SÚJB (State Office for Nuclear Safety), thus suggesting an unequal distribution of responsibilities. Not much progress has therefore been made to organize long term disposal facilities for radioactive waste. The regulatory regime for managing radioactive waste in the Czech Republic appears to be fragmented and indirect.

The **German** nuclear policy settings are complex – an outcome of the constitutional arrangements and the associated consultative decision making processes. Accordingly, it is not surprising to note Germany's anti-nuclear stance. After debate on nuclear energy over the last forty years, the public opinion is firmed against it now. In June 2011, Germany became the first industrialized country to abandon nuclear energy and explore other alternatives. Public opinion has played a very important role in political decision making. The SPD and Green parties regard nuclear energy as an option which should be used until 2022 [8.8]. The socialist party, Die Linke, however, believes in the immediate abandoning of nuclear energy. The conservative parties, CDU/CSU and the liberal party (FDP) believe that nuclear energy is the only option in meeting Germany's commitment of reducing GHG emissions.

Furthermore, the anti-nuclear beliefs in Germany have aggravated owing to the negligence in the maintenance and supervision of existing radioactive waste disposal facilities in abandoned mines. For instance, in 1965, the Asse II mine was turned into a temporary storage and research facility for radioactive waste. Later, this site became a permanent disposal site for nuclear material. However, in June 2011, news broke that brine, known to be leaking from the mine since 1988, is radioactive – at the level of eight times above safe levels [8.31]. In the case of the Asse radioactive waste storage site, the German ministers agreed to monitor the mine under the jurisdiction of the federal environment ministry [8.31]. However, this has raised further concerns about existing regulatory settings at the state level and their appropriateness for monitoring radiation levels at waste sites.

Moreover, a safe, final, long term disposal solution for radioactive waste is yet to be found. Also, conflict of interests between the national government, the federal government and the operating company of the waste management facility delayed the preparations for the establishment of waste complexes in Germany [8.32]. For instance, both the Asse II and

Morsleben waste sites are affected by problems caused by the operator of the repositories. However, the public was not consulted about site selection. It was also alleged that the operator cheated on inventory and safety issues by not following the nuclear law which includes provisions of public consultation for the final site selection of the repository facilities. Thus, arguments about conflict of interest and non-compliance with the nuclear law have proven to be major barriers for establishing a safe nuclear disposal facility in Germany.

The institutional and regulatory arrangement for nuclear energy in Germany – in concord with its fragment policy settings – are typified by the multiplicity of organizational involvement, regulatory overlaps and inconsistencies.

The **Lithuanian** energy policy settings are a reflection of the country's historical past. They appear to be overwhelmingly burdened by domestic imperatives and international pressures arising primarily from Lithuania's accession to the EU. For example, in 2007, the Head of VATESI indicated the need for revising the regulatory documentation by assessing and taking into account the experience of other countries (Finland in particular) [8.33]. He further highlighted that VATESI plans to implement its new licensing process in 2011, which will optimize the regulatory challenges, also adding that, "No one in Lithuania has ever done this before. Licensing of the new NPP is a completely different story" [8.33].

The development of cohesive and stable institutional and regulatory settings for nuclear energy in Lithuania also appears to be hindered by the lack of essential infrastructure. For example, according to the Visaginas Nuclear Power Plant (VAE), "A certain infrastructure is essential for the construction of the new power plant" [8.33]. Lithuania also appears to suffer from the lack of scientific expertise in radioactive waste disposal. The Lithuanian Radioactive Waste Management Agency (RATA), the main agency, is relatively new and lacks the experience to plan the siting, design, construction, commissioning and operation of a near surface disposal facility for radioactive waste in a timely manner.

The policies of the **Republic of Korea** are positively inclined towards nuclear power. A major emergent problem faced by the Republic of Korea is the accumulation of spent nuclear fuel, soon likely to outstrip the country's disposal capacity for high level radioactive waste [8.34]. This dilemma has been exacerbated by some factors unique to the Republic of Korea, such as high population density, making it rather difficult to build a single large permanent underground repository for radioactive waste [8.34]. The location next to the nuclear armed Democratic People's Republic of Korea and its status as a major USA ally and a long time partner in nuclear development have also constrained its choices when it comes to disposing of spent nuclear fuel [8.34].

The Republic of Korea has actively sought to develop spent nuclear fuel disposal mechanisms ever since the onset of its nuclear program in 1978. Its earlier measures were aimed at finding a site for the disposal of LILW, and an interim storage facility for spent nuclear fuel located away from reactor sites. These earlier decisions were based on historical and political circumstances of the country at that time [8.34]. It was further argued that it would be easier to decommission nuclear plants if no interim spent fuel storage sites were located at the facilities. Such decisions were made without the involvement of the general public. Subsequent attempts to locate a site for disposal therefore faced significant public opposition [8.34].

Public opposition to radioactive waste disposal sites in the Republic of Korea has been more vociferous and long standing than in many other countries, leading on at least one occasion to rioting. This has led the government to regularly unveil and then scrap proposed new sites for disposing waste material and to reach a compromise earlier to dispose of low level waste that may have made even more intractable the problem of disposal of high level waste [8.34].

In 1996, the government decided to split responsibilities for dealing with radioactive waste. This was, however, opposed by the communities. The government therefore took a new approach that helped it secure a new site for LILW. This new approach pledged that no additional spent fuel storage facilities would be located in the host area. It also included a provision of several additional incentives provided for the people who resided in that community [8.34]. Such a process enabled the government to begin with the construction of the facility in 2007, but it raised the cost of the project. It was estimated that the potential cost of investment in a final disposal site for high radioactive waste would be much higher and would require more space. However, no approach has been finalized yet in this regard.

In **Switzerland**, the HSK is the implementing organization for radioactive waste disposal; it is also closely linked to the operator of nuclear power plants [8.14]. This has created perceptions of conflict of interest among the public. Thus, it is a challenge for the regulator to be regarded by the public as neutral and independent authority with the unique objective to ensure safety [8.14].

The site for geological disposal of radioactive waste in Switzerland is approved only after assessing the safety and technical feasibility and adhering to any community concerns. Hearings show that local authorities and the general public would like to see a set of clear quantitative and easily measurable criteria regarding the suitability of a site [8.14]. However, in reality, the selection of a site for disposal activity is based on several parameters, and these parameters are not precisely known at the start of the process and are determined by subsequent site investigations and characterization. Thus, regulators argue that, at the beginning of the procedure, the criteria for selection can only be qualitative (rather than quantitative). Such a situation is, however, difficult to explain to the public and hence it is difficult to earn its acceptance [8.14].

CO_2 Disposal

In view of the criticality of fossil fuel in the electricity economy complex in **Australia**, there is bipartisan support for CCD. The policy settings, institutional and regulatory arrangement are, however, less developed.

In 2006, the Queensland (QLD) State government, the Australian government and other private industries jointly funded the ZeroGen's project, as a pre-feasibility study of low emission technologies for coal based electricity generation. However, in 2010, the State government announced its decision to scrap the project because the projected generation costs were too high and there was significant uncertainty in finding CO_2 disposal sites near the project site. The project was ultimately passed on to the industry run Australian Coal Association. It is expected that this would delay the construction by another five years [8.35].

The existing regulatory regime does not provide clarity in the treatment of permit areas which overlap or lie in multiple jurisdictions, for example, disposal areas close to inshore, where both Federal and State jurisdictions meet [8.36]. Such a situation can give rise to bureaucratic overload, as the applicant has to seek approvals from both the jurisdictions and, owing to the short licensing terms, the procedure has to be repeated in a few years. Moreover, there are no independent authorities for monitoring and settling disputes and licensing challenges. Other issues include the difference in the treatment of long term liabilities between certain states and the Commonwealth, thus implicating issues for cross boundary disposal projects in Australia.

In the **Czech Republic**, the conflict of interest amongst the two dominant ministries, namely, the Ministry of Industry and the Ministry of Environment, was believed to be one of the reasons for not transposing the EU CCS Directive in domestic laws. The Ministry of Industry proposes a general ban on CO_2 disposal, whereas the Ministry of Environment completely supports the transposition of the CCS Directive [8.37]. Further, disagreements have been observed regarding the form of implementation of the CCS law, through the introduction of separate new laws or through amendment to the existing ones. The law was finally accepted in 2012 as a separate Act (Act No. 85/2012 Coll.), changing the responsibilities of several other Acts (the Act about Environmental Impact Assessment No. 100/2001; the Act about Waste No. 185/2001 Coll., Water Act No. 76/2002 Coll. etc.).

Other issues observed are the ongoing discrepancies between the public and the government about safety issues related to geological disposal of CO_2 and the possibility of insufficient disposal capacity in the Czech Republic [8.37].

In **Germany**, the opinions on the conclusion of the CCD law diverge – both at public and decision making levels. The draft CCD legislation is very controversial in Germany. The Federal Ministry of Economics and Technology (BMWi) asserts that the demonstration projects are necessary to assess whether CCD could contribute to climate protection [8.38]. The draft act contains a clause pursuant to which the federal states can designate areas for CCD pilot projects as well as areas in which such projects are not allowed. However, this decision was fiercely opposed by the state of Brandenburg, with the argument that it would give other states with more suitable disposal locations the right to opt out of exploring a potential climate protection option [8.38].

This issue is important because, in the past, widespread discontentment had forced the government to withdraw its first draft of CCD legislation. The discontentment was primarily related to the risk of leakage, pollution of drinking water, long term safety and liability, as well as land owner rights and public consultations. A combined study on the public awareness on CCD was conducted by the Wuppertal Institute, Forschungzentrum Jülich, Fraunhofer Institute and BSR Sustainability GmbH carried out on behalf of BMWi. Their empirical analysis suggested that at present the majority of the public in Germany is neither for nor against CCD because the level of awareness among the public is very low or virtually non-existent.

The CCD policies and laws in Germany are in their early stages of development and the disposal laws are extracted from the mining laws. However, the German mining law was not drafted with CO_2 disposal in mind, because CO_2 injection into the earth is not a traditional mining activity [8.38]. With the lack of legal basis and demonstration projects already initiated, the exploratory work for potential CCD disposal in salt caverns in the state of Brandenburg currently relies on the mining law regime for brine exploration. However, the application of the mining law to CCS law will provide some challenges during the planning and operational stages.

Until recently, the focus on CCD in **Lithuania** has essentially been technical in nature, exploring the possibility of geological disposal in the Baltic region. Studies have also covered the utilization of CO_2 for enhanced oil recovery in the western part of Lithuania and it is believed that CCD might be a long term solution for Lithuania's commitments to reduce its emissions. However, limited attention has been given to the institutional and regulatory changes needed to promote this technology. The legislation to comply with the CCS Directive so as to carry out CCD projects in Lithuania therefore stays undeveloped. As CCD is a comparatively new technology for Lithuania, the major challenge faced by policymakers is likely to be the transposition of European level initiatives into domestic laws.

The **Republic of Korea** is currently in the process of developing policies on CCD. Some of the issues are unclear in the existing Korean legislation, such as the status of captured CO_2, would it be treated as a waste or a pollutant? The current legislative frameworks for the exploration of potential disposal sites for purposes other than CCD provide general rights and obligations which could govern approval conditions similar to that of CCD. However, it is not clear whether they will be applicable for CCD as well [8.23]. Moreover, there are no specific policies, integrated or generally applicable laws governing the injection and pre-closure of CO_2 sequestration formations. Thus the existing frameworks are being used as models for CCD regulation in Korea but are not likely to be applicable directly to CCD. It is therefore necessary for the government to establish a comprehensive basic law that uniformly and systematically regulates CCD projects from the approval stage to the post-closure management stage [8.23].

There are currently no policy or regulatory frameworks for CCD in **Switzerland**.

8.3. COMPARATIVE ASSESSMENT

This section presents comparisons of policies, regulations and institutional settings across the countries included in this study based on the material presented in sections 8.1 and 8.2. The comparative analyses are organized into tables. Key aspects of the policy, regulatory and institutional settings are summarized in Tables 8.7, 8.8 and 8.9.

8.4. CONCLUSIONS

The main conclusions based on the comparative overview portrayed in Tables 8.7, 8.8 and 8.9.

Nuclear and fossil fuel based power with the provision of CCD are attractive propositions for reducing GHG emissions and hence redressing the climate change challenge. Much of the existing analysis on these technologies focuses, primarily, on developing estimates of the technical potential offered by these technologies and their cost effectiveness. Further, much of the assessments have tended to be limited to the generation segment of the power industry and, to a somewhat lesser extent, to the transportation segments.

TABLE 8.7. CROSS COUNTRY COMPARISONS OF RADIOACTIVE WASTE DISPOSAL

	AUSTRALIA	CZECH REPUBLIC	GERMANY	LITHUANIA	REPUBLIC OF KOREA	SWITZERLAND
POLICY	No defined nuclear policy; NW -mainly from research reactor; reprocessed for storage and disposal	No coherent state policy on reprocessing NW; economically in-feasible	Energy policies-consistent with EU law; Initial policy- reprocess spent fuel, Now- direct disposal	Policies consistent with EU Laws; LLW disposal in place; Ongoing research-HLW disposal	Fuel reprocessing -USA influence; LLW disposal options in place; Ongoing research-HLW	Policies support both reprocessing and direct disposal of NW
	Nuclear power- no economic role	Nuclear power- dominant economic role	Nuclear power- dominant economic role; phase-out by 2022	Nuclear plays minor role in electricity sector but faces Energy Security challenge	Nuclear power important for economic prosperity	Nuclear power-dominant role in electricity sector
	Meeting GHG emissions target- issue without nuclear energy	Meeting GHG emissions target –a non-issue	Meeting GHG emissions target- issue with nuclear phase-out	Meeting GHG emissions target- an issue without Ignalina NPP	Meeting GHG emissions target- a major issue	Meeting GHG emissions target –a non-issue
	Opinions for NPP and NWD – diverse at federal and state levels	No political issues observed	Opinions for nuclear phase-out differ amongst political parties	No political issues observed	Opinions diverse amongst political parties	No political issues observed
	Public - highly opposed to NWD	Community- opposed to NWD; has influence in siting	Public -highly anti-nuclear	No opposition faced from general public	Public is highly opposed to NWD	Policy making involves public participation; public-pro nuclear
Regulation	Laws- well focused, covers all aspects, influenced by International Treaties	Laws- ill defined, highly influenced by International arrangements (EU)	Laws- inconsistent, need to be updated, highly influenced by International Treaties	Laws- inconsistent, need to be updated as per international standards	Laws- highly influenced by US and other neighbouring countries and well defined	Laws- recently updated and well focused, limited external influence
	Regulations directly aligned with NWD	Regulations fragmented and indirect	Significant overlaps and indirect	Limited exposure to licensing regime and others	Regulations directly aligned with NWD	Regulations directly aligned with NWD
	Public participation limited in site selection and other activities	Too much public participation, prove to be hindrance	Public anti-nuclear, but limited involvement in site selection and other activities	Limited public involvement in NWD activities	Public anti-nuclear, but limited involvement in site selection	Public involvement a noticeable feature
Institutions	ANSTO – implementer; ARPANSA- regulator;	SÚJB – excessive regulatory burden; RAWRA- too much government intervention	Lack of responsibilities at state and local level; Federal – intervention a common feature	Lack of communication between regulatory authorities; Lack of expertise- newness of RATA	Independent regulator and implementer	Regulatory authority is also known as implementer
	Institutional settings- well defined and managed	Institutional settings- need to be improved	Institutional settings- well defined, poorly managed	Lack of incentive for investment in NPP, indicating poor structural arrangements	Well defined institutions, poor management hence overspending	Structural arrangements need to be improved; Public less aware of institutions
	Institution overlap – significant at Federal and State level causing bureaucratic overload	Institutions overlap- between SÚJB and RAWRA	Institutions overlap – owing to poor performance at State level	No overlap observed	No overlaps observed	No overlaps observed

TABLE 8.8. CROSS COUNTRY COMPARISONS of CO_2 DISPOSAL

	AUSTRALIA	CZECH REPUBLIC	GERMANY	LITHUANIA	REPUBLIC OF KOREA	SWITZERLAND
Policy	Government committed- reducing GHG emissions	Low GHG emissions, high per capita emissions	Self imposed goals to reduce GHG emissions even more	Low GHG emissions; Energy security- a challenge	Need more stringent policy to reduce emissions	GHG emission not a challenge, committed to reduce further
	Policy commitment for CCS- bipartisan support	Obliged under EU law to transpose CCS Directive	Committed to CCS, besides EU obligation	Obliged under EU law to transpose CCS Directive	No CCS policy; focus- higher economic growth	No CCS policy
	Political discrepancies exist on GHG reduction potential with CCS technologies	No political issues observed	Political opinions differs- few states have opted out of CCS clause	No political issues observed	Political differences exist	No political issues observed
	Public oppose CCS owing to potential leakage issues	Public highly opposes CCS owing to safety issues	Public highly opposes CCS owing to safety issues and others	Public opinion has been neutral to CCS activities	Public opinion has been neutral to CCS activities	Public involvement plays an important role in policy making and is neutral to CCS technologies
Regulation	Laws- some aspects adopted from mining and petroleum laws, highly influenced by organizations and countries pro CCS	Limited attention given to development of CCS legislation	Storage laws extracted from mining laws	Undeveloped CCS legislation	Undeveloped CCS legislation, framework extracted from mining and waste laws	Undeveloped legislation
	Issues concerning access and property rights, long- term liability and transboundary	Issues concerning limited storage capacity and financial resources to support R&D	Issues concerning limited storage capacity	Information Gap	Information Gap	Information Gap
	Public participation limited	No information on public involvement	No information on public involvement	No information on public involvement	No information on public involvement	No information on public involvement
Institutions	Settings- gradual evolution with pilot projects	Settings – ill defined, conflicting interests	Settings – ill defined	Settings – ill defined	Settings – ill defined	Settings – ill defined
	Institution overlap – significant causing bureaucratic overload due to transboundary issues	No overlaps observed	No overlaps observed	No overlaps observed	No overlaps observed	No overlaps observed

TABLE 8.9. CROSS COUNTRY COMPARISONS OF RADIOACTIVE WASTE AND CO_2 DISPOSAL

	AUSTRALIA	CZECH REPUBLIC	GERMANY	LITHUANIA	REPUBLIC OF KOREA	SWITZERLAND
Policy	No defined nuclear policy Highly fossil-fuel dependent, hence CCS pro	Nuclear dependent economy but obliged under EU Laws to transpose CCS	With nuclear phase-out planned – considering CCS options and obliged under EU laws	Less nuclear dependent economy - considering CCS with closure of NPP and obliged under EU laws	Relies on nuclear for economic growth and GHG reduction No CCS policies	Nuclear dependent economy No CCS policies
	Public and political parties oppose both	Public opposed to both technologies	Public and political opposed to both technologies	No public opposition to both technologies	Fierce public opinion on nuclear and no opposition to CCS	Neutral public opinion to both
Regulation	Well defined laws on NWD	Fragmented and indirect NWD regulations	Inconsistent NWD regime	Inconsistent NWD regime	Well defined laws on NWD	NWD Laws updated and well defined
	CCS still developing, adopted from mining and petroleum laws	Ill-defined CCS Law	CCS regime adopted from mining laws	Undeveloped CCS regime	Undeveloped CCS regime, adopted from mining and waste laws	Undeveloped CCS regime
	Limited public participation for both	Too much public participation for NWD	Limited public involvement for NWD	Limited public involvement for NWD	Limited public involvement for NWD	Public involvement a noticeable feature for NWD
Institutions	Well developed institutions for NWD activities CCS projects regulated by existing institutions under mining regime	Ill defined institutions and managements for both	Well-defined settings for NWD, poorly managed Ill-defined settings for CCS	Ill defined settings and managements for both	Well defined structural arrangements, poor management of NWD Ill-defined settings	Structural arrangements ill-defined for NWD Ill-defined settings for CCS
	Significant institution al overlap in both	Significant overlap for NWD	Significant overlap for NWD	No overlaps observed	No overlaps observed	No overlaps observed
Classification	Radioactive wastes classified into LLW, ILW and HLW; Classification of CO_2 varies at industrial level as industrial product and at regulator level as waste	Radioactive wastes classified into LLW, ILW and HLW; Classification of CO_2 is not clear	waste is divided into two categories: heat and non-heat generating waste; Legal status of CO_2 not defined	Disposal of waste depends upon classification -LLW,ILW, HLW and spent nuclear fuel; Legal status of CO_2 not defined	Radioactive wastes classified into LLW, ILW and HLW; Status of CO_2 is as a pollutant like other GHG gases	Waste is classified as HLW, Alpha toxic waste , ILW and LLW; Legal status of CO_2 not clear

Relatively little attention has been paid to the analysis of the institutional aspects relating to radioactive waste and CO_2 disposal. What is particularly apparent in these analyses is the lackadaisical effort devoted to analysing the influence that policy, institutional and regulatory settings may exert in terms of defining the extent of the uptake of nuclear energy and fossil with CCD options. After all, many of the major concerns about these two technologies relate to their disposal and the consequential medium to long term environmental impacts. The analyses undertaken in this chapter have demonstrated the criticality of this argument.

While the policy, regulatory and institutional settings are well defined for radioactive waste disposal, for CO_2 disposal they are either undeveloped or underdeveloped in most of the countries included in this project. Further, for CO_2 disposal (and for CCD, more generally), considerably more analysis is required. For example, it would be necessary to define the legal status of CO_2 because in some of the countries, it is treated as an industrial product, whilst in others it is considered as a waste. In contrast, radioactive waste laws classify waste into various categories, and their final disposal and safety assessments are carried out on the basis of a near universal classification.

From a policy perspective, nuclear energy plays a major role in the electricity economy complex in all countries considered in this chapter, except Australia. However, most of the countries considered face a major challenge in safely disposing of their radioactive waste.

Other areas that are poorly developed include the regulatory arrangements for long term liability for the disposed CO_2 and the property rights related to the exploration of potential sites for CO_2 disposal.

Information gaps were observed in the institutional settings for CCD in Germany, Lithuania, the Republic of Korea and Switzerland and in the regulatory settings in the Republic of Korea and Switzerland.

Public awareness and consultation plays an important role in the policy and regulatory design for both technologies. Analysis in this chapter suggests that most of the acts and laws have provisions for public consultation, but such consultation does not take place in reality in most countries. This has significantly contributed to the increases in project duration and costs, and to the timely evolution of policy, institutional and regulatory design.

Much of the cost analyses of the two technologies have focused on direct costs. The issue of transaction cost has been paid scant attention. This could lead to gross underestimation of costs and significantly affect the assessment of the potential these technologies offer in redressing the climate change challenge. Thus the assessment frameworks for comparing CO_2 and radioactive waste disposal should include aspects such as costs of changes in existing institutions and regulatory settings, costs of specialists or training in licensing and safety issues – more generally, the transaction costs.

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LIST OF ABBREVIATIONS

3E	Energy Economy Environment
ACT	Australian Capital Territory
ADP	Ad Hoc Working Group on the Durban Platform for Enhanced Action
AEA	Atomic Energy Act
AECL	Atomic Energy of Canada Limited
AERB	Atomic Energy Regulatory Board
AkEnd	Working Group for Selection Process for the Final Disposal Sites
ANSTO	Australian Nuclear Science and Technology Organization
ARGONA	Arenas for Risk Governance
ARPANSA	Australian Radiation Protection and Nuclear Safety Act
atm	atmosphere
BAS	Bulgarian Academy of Sciences
BfE	Federal Agency for Energy
BfS	Federal Agency for Radiation Protection
BGR	Federal Institute for Geosciences and Natural Resources
BIP	borehole image processing
BMU	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
BMWi	Federal Ministry of Economics and Energy
BWR	boiling water reactor
CANDU	Canada Deuterium Uranium
CaO	calcium oxide
CARMA	Carbon Management in Power Generation
CCD	CO_2 capture and disposal
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CDU	Christian Democrat Union
CEZ	Czech Power Company
CF	certified framework
CH	Switzerland
CLR	CO_2 leakage risk
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
CO_2	carbon dioxide
COP	Conference of the Parties

CRP	coordinated research project
CUAEPP	Bulgarian Nuclear Safety Authority
DALY	disability adjusted life year
DBE	German Society for Building and Operating Final Disposal for Wastes, Ltd.
DE	Germany
DETEC	Federal Department for Environment, Transportation, Energy and Communication
DFAT	Department of Foreign Affairs and Trade
DOE	Department of Energy
DOGF	depleted oil and gas fields
DRET	Department of Resources, Energy and Tourism
EBRD	European Bank for Reconstruction and Development
EC	European Commission
ECBMR	enhanced coal bed methane recovery
ENSI	Swiss Federal Nuclear Safety Inspectorate
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EPBC	Environment Protection and Biodiversity Conversation
ERAM	Morsleben Repository for Radioactive Waste
ETS	emissions trading scheme
ETT	effective trapping threshold
EU	European Union
EURATOM	European Atomic Energy Community
FDP	Liberal Democrat Party
FEP	features, events and processes
FOEN	Swiss Federal Office for the Environment
FTT	fracture toughness test
GCCSI	Global Carbon Capture and Storage Institute
GESTCO	geological storage of CO_2
GFZ	German Research Centre for Geosciences
GHG	greenhouse gas
GIS	geographical information system
GPS	global positioning system
Gt	billion t
GTCC	gas turbine combined cycle
GW	gigawatt

HCD	hydraulic conductor domains
HFO	heavy fuel oil
HLW	high level waste
HRD	hydraulic rock domains
HSD	hydraulic soil domain
HSK	Principal Nuclear Safety Division
HTU	hydraulic testing unit
IAEA	International Atomic Energy Agency
IATA	International Air Transport Association
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
ILW	intermediary level waste
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing
IS	Indian Standard
JRC	Joint Research Centre
KAERI	Korea Atomic Energy Research Institute
KBS	nuclear fuel safety
KEG	Swiss Nuclear Law
KHNP	Korea Hydro and Nuclear Power Company, Ltd.
KNOC	Korea National Oil Corporation
KRMC	Korea Radioactive Waste Management Corporation
KRS	Korean reference disposal system
kt	thousand t
kW·h	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LILW	low and intermediary level waste
LISS III	Linear Imaging Self Scanning Sensor III
LLW	low level waste
Ma	million years
MCMPR	Ministerial Council on Mineral and Petroleum Resources
mD	millidarcy
MgO	magnesium oxide

MKE	Ministry of Knowledge Economy
MOE	Ministry of Environment
MOST	Ministry of Education, Science and Technology
MOX	mixed oxide
MPa	megapascal
MSK	Medvedev-Sponheuer-Karnik
mSv	millisievert
Mt	million t
MW	megawatts
MW·h	megawatt hour
Na	sodium
NA_2O	sodium oxide
NAGRA	National Cooperative for the Disposal of Radioactive Waste
NEA	Nuclear Energy Agency
NGO	non-governmental organization
NIMBY	not in my back yard
NLECI	National Low Emissions Coal Initiative
NPP	nuclear power plant
NSDF	near surface disposal facilities
NSW	New South Wales
NT	Northern Territory
OECD	Organisation for Economic Co-operation and Development
OEH	Office of Environment and Heritage
OFEN	Federal Energy Office
OFSP	Federal Office of Public Health
OMM	upper marine molasses
OSM	upper freshwater molasses
PAF	potentially affected fraction
PDF	potentially disappeared fraction
PEL	permissible exposition limits
PFL	Posiva flow log
PHWR	pressurized heavy water reactor
PWR	pressurized water reactor
QLD	Queensland
RATA	Radioactive Waste Management Agency

RAWRA	Radioactive Waste Repository Authority
RBMK	high power channel type reactor
RINOVA	Risk perceptions, public communication and innovative governance in knowledge society
RW	radioactive waste
SA	South Australia
SF	spent fuel
SFOE	Swiss Federal Office of Energy
SKB	Swedish Nuclear Fuel & Waste Management Company
SL ILW	short lived intermediary level waste
SNF	spent nuclear fuel
SPD	Social Democratic Party
SS	stainless steel
SÚJB	State Office for Nuclear Safety
TAS	Tasmania
tHM	ton of heavy metal
TMH	thermal mechanical hydraulic
UCTE	Union for the Co-ordination of the Transmission of Electricity
UNFCCC	United Nations Framework Convention on Climate Change
USM	lower freshwater molasses
VAE	Visaginas Nuclear Power Plant
VATESI	State Nuclear Power Safety Inspectorate
VET	vulnerability evaluation framework
VIC	Victoria
VSP	vertical seismic profile
WA	Western Australia
WIPP	Waste Isolation Pilot Plan
WWER	Water Water Energy Reactor
ZEP	Zero Emissions Platform

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