Comparing the Geological Disposal of Carbon Dioxide and Radioactive Waste: Introduction and Overview

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Abstract Fossil fuels will remain the backbone of the global energy economy for the foreseeable future. The contribution of nuclear energy to the global energy supply is also expected to increase. With the pressing need to mitigate climate change and reduce greenhouse gas emissions, the fossil energy industry is exploring the possibility of carbon dioxide disposal in geological media. Geological disposal has been studied for decades by the nuclear industry with a view to ensuring the safe containment of its wastes. Geological disposal of carbon dioxide and that of radioactive waste gives rise to many common concerns in domains ranging from geology to public acceptance. In this respect, comparative assessments reveal many similarities, ranging from the transformation of the geological environment and safety and monitoring concerns to regulatory, liability and public acceptance issues. However, there are profound differences on a broad range of issues as well, such as the quantities and hazardous features of the materials to be disposed of, the characteristics of the targeted geological media, the site engineering technologies involved and the timescales required for safe containment at the disposal location. There are ample opportunities to learn from comparisons and to derive insights that will assist policymakers responsible for national energy strategies and international climate policies.

Keywords Geological disposal • Carbon dioxide • Radioactive waste • Comparative analysis • Climate change mitigation • Sustainable energy development

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1 Introduction

In the second half of the last century the use of fossil fuels, especially coal and oil, has gone through two major technology transformations, first in the developed countries, followed by the economies in transition as well as in more affluent developing countries. The first transformation was triggered by local/regional air pollution problems (urban smog with severe visibility degradation and human health impacts) and entailed the removal or wider dispersion of heavy hydrocarbons (C_xH_y) from stack gases. The second change was prompted by continental-scale pollution problems that involved long-range transport of air pollutants (mainly SO_x) causing material corrosion, forest degradation and the acidification of water bodies. The response to both transitions encompassed a set of technologies ranging from pre-combustion fuel treatment to flue gas scrubbing to reduce the emissions of pertinent compounds as well as fuel and technology switching. The increasing concern over anthropogenic climate change and the need to reduce greenhouse gas (GHG) emissions poses the next challenge to the fossil fuel industry. If large reductions of GHG emissions are necessary over the next few decades, the viability of fossil fuels will depend on the possibility and prospects of preventing the release of carbon dioxide (CO_2) into the atmosphere by capturing and disposing of it in geological formations. CO_2 capture and disposal (CCD) has emerged as one of the principal fields of scientific research and technological R&D.

Over the same time frame, nuclear energy has been pursued by many countries for a variety of reasons, ranging from fast growing energy demand to energy supply security and, more recently, as part of climate change mitigation strategies. The safe disposal of the resulting radioactive waste (RW) has been one of the main predicaments from the beginning, and it remains an issue that the nuclear industry needs to resolve in order to improve the prospects for nuclear energy to contribute to resolving the enormous energy challenges the world faces in this century. Over the past 2 decades, major scientific and technological advances have been made towards the safe temporary storage and final disposal of RW. The disposal of RW in geological media is considered by most scientists and engineers engaged in the issue to be a safe and viable method for isolating it from the hydrosphere, the atmosphere and the biosphere.

Geological disposal of the waste products (CO_2 and RW) establishes a curious link between the fossil fuel and nuclear energy industries. The question arises whether, despite the profound differences, at least at first sight, there is any chance to learn from comparing the diverse array of issues involved and what the possibilities are for sharing experience and transferring lessons between the two fields. This chapter introduces a book that is intended to explore these questions across relevant thematic areas and in selected geographical regions. It presents the broader context of global energy challenges and the potential role of fossil fuels (combined with CCD) and of nuclear power (combined with RW disposal) in long-term climate change mitigation and sustainable energy development.

It is important to clarify the terminology used here right at the outset. The emplacement of CO_2 in geological formations is widely called ‘storage’. This is a somewhat misleading euphemism because the primary meaning of the word 'storage' is the action of putting something away for future use whereas it is not foreseen to use the disposed CO_2 ever again. Therefore, most chapters in the book use 'disposal', but some authors prefer to adhere to 'storage' or 'sequestration' (a widely used term especially in the North American literature) and these preferences are respected. Hence, in connection with CO_2 the three terms, geological disposal, storage and sequestration are used interchangeably throughout the book. With regard to RW, there is more clarity: 'storage' is used for the keeping of spent fuel and other RW in temporary storage facilities even if such arrangements last for decades in many cases, while the term 'disposal' is used for permanent emplacement in geological formations, even if it is intended to leave open the option of retrievability for 100 years or longer.

The next section presents a short summary of the global energy challenges for the twenty-first century as the broader context for this book. This is followed in Sect. 3 by an outline of the key issues pertinent to the comparative assessment of CO_2 and RW disposal. An overview of the thematic and regional chapters (all peer-reviewed by at least three referees) is presented in Sect. 4. Section 5 summarizes the most important points raised in this chapter.

2 Energy Challenges for the Twenty-First Century

Energy is generally recognized as a central issue in sustainable development. Several high-level conferences and declarations have emphasized that the provision of adequate energy services at affordable costs, in a secure and environmentally benign manner and in conformity with social and economic developmental needs is an essential element of sustainable development. Reliable energy services are an important precondition for investments that bring about economic development. Among other things, they facilitate the learning and study and improved health care that are crucial for developing human capital. They also promote gender equity by allowing women to use their time for more productive activities than collecting firewood, and social equity by giving the less well-off the chance to study, thus providing a possible escape from poverty. Energy is therefore vital for alleviating poverty, improving human welfare and raising living standards. Yet, worldwide, 2.4 billion people rely on traditional biomass as their primary source of energy and 1.6 billion people do not have access to electricity (UNDP 2005), and this severely hampers socioeconomic development.

All recent socioeconomic development studies forecast major increases in energy demand, driven largely by demographic and economic growth in today's developing countries. Of the world's 6.8 billion people, about 82% live in non-OECD countries and consume only 53% of global primary energy. Alleviating this energy inequity will be a major challenge. A growing global population will compound the problem. The medium variant of the latest projection by the United Nations estimates an additional 1.5 billion people by 2030, and another 840 million by 2050, bringing the world's population to about 9.15 billion by the middle of this century (UN DESA 2009).

It is also anticipated that the rising population will enjoy increasing economic welfare over the next decades. According to the World Bank (2009a), after the projected meagre 0.9% global GDP growth in 2009, it is expected to rebound to 2% in 2010 and 3.2% in 2011. Developing countries are projected to expand by 4.4% (2010) and 5.7% (2011). Over the long term, the World Bank (2009b) projects a 3.1% average annual growth rate for the world economy up to 2015 and 2.5% between 2015 and 2030. Developing countries will grow fastest, while OECD countries will grow at the slowest rate. Per capita incomes in developing countries are projected to triple from US$1,550 in 2004 to US$4,650 in 2030.

In its World Energy Outlook (WEO) 2008 (IEA 2008a), the OECD International Energy Agency (IEA) adopts the population projection developed by the United Nations Department of Economic and Social Affairs (UN DESA) and makes similar assumptions as the World Bank about longer term economic development. World population is estimated to increase to 8.2 billion by 2030, while the global economy is assumed to grow at an annual average rate of 4.2% up to 2015 and 2.8% between 2015 and 2030. Based on these two main drivers of energy demand and additional assumptions about technological development and resource availability for the energy sector, the IEA projects in its Reference Scenario that world total primary energy demand will grow to over 17 gigatonnes of oil equivalent (Gtoe) by 2030 (IEA 2008a) and, according to the extended Reference Scenario presented in Energy Technology Perspectives (ETP) 2008 (IEA 2008b), it will exceed 23 Gtoe in 2050 (see Fig. 1).

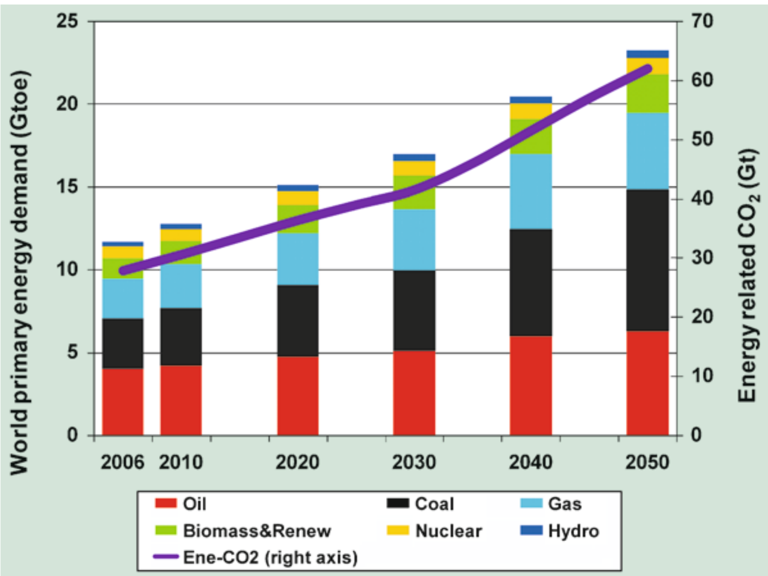

Fig. 1 Global primary energy sources (*left axis*) and energy-related CO_2 emissions (*right axis*) in the IEA's reference scenarios (Based on IEA 2008a, b) (*see* Colour Plates)

The ETP study (IEA 2008b) presents the global energy prospects up to the middle of the century. The most notable changes anticipated for the next half century in the IEA Reference Scenario include the following:

- Coal is expected to surpass oil as the largest primary energy source by 2040 due to the persistent strong growth in demand for electricity in coal-rich countries such as China and India.
- Gas is estimated to level out at around 4.5 Gtoe by the middle of the century.
- Despite a 31% increase in volume between 2005 and 2050, the nuclear share in the global primary energy balance is projected to decline from 6.3% in 2005 to 4.8% by 2030 and to 4% by 2050.

The climate change implications of the Reference Scenario are severe. Energy-related CO_2 emissions, the largest component of global GHG emissions, will have increased by 55% in 2030 and by 130% in 2050 relative to 2005. Assuming that other GHGs increase at comparable rates, this would put the Earth on track towards atmospheric GHG concentrations on the order of 800 ppm CO_2 equivalent and an equilibrium warming of over 5°C in terms of global mean temperature increase above the pre-industrial level (IPCC 2007a). Thus these trends stand in sharp contradiction to the declaration issued by the Group of Eight (G8) summit in 2009 on the need to keep global mean temperature increase below 2°C, and point to the urgent requirement for deploying low-carbon technologies.

In addition to the staggering increases in demand for all forms of energy, particularly electricity, and the need to reduce GHG emissions, there are several other issues on the current energy policy agendas of many countries that nuclear power and coal-based electricity using CCD might contribute to resolving.

The first factor is the price of oil and gas energy sources. The rate of infrastructure development in resource extraction and delivery in key supply regions is lagging behind the fast growing energy needs. This exerts a sustained upward pressure on international oil and gas prices even if one takes into account the speculative bubble that affected commodity prices and culminated in mid-2008. This in itself is a strong motivation for countries that depend on high shares of imported fuels for their electricity generation to look for substitutes. Political conflicts in key supply regions exacerbate the price pressure and raise severe concerns over the security of supply per se, even at high prices. This is yet another reason for considering alternative electricity sources.

Energy importing developing countries tend to be more concerned about the sustained high price level because of the prospect of its severely increasing their energy import bills, affecting their current account balances and undermining the competitiveness of their export industries. In most developed countries (except those with very small energy resource endowments) energy is a relatively smaller fraction of the total import bills and the energy content of exports is lower. These countries are more concerned about direct losses due to supply disruptions, especially if these might render expensive capital and labour capacities idle for some time.

Another, but closely related, factor is price volatility. All elements of the energy supply infrastructure are long lived. Energy intensive industries base their investment decisions on cautious expectations about future energy and electricity prices. A reasonable degree of stability and predictability of resource prices is crucial for such decisions because hedging against large price fluctuations might be vastly expensive.

In many countries continued reliance on large and cheap domestic coal reserves could help alleviate energy security fears, but the use of currently prevailing technologies would aggravate the climate problem. In other countries nuclear power could help mitigate supply security concerns and reduce GHG emissions at the same time. The choice between establishing or expanding coal-based power generation combined with CCD, or nuclear electricity accompanied by the need to find a means of safe disposal for the resulting RW will be influenced by many factors and will depend on natural resource and environmental endowments as well as on social, economic and political preferences.

3 Why Compare CO_2 and Radioactive Waste Disposal?

This section delineates the considerations that motivated the initiation of the comparative assessments and the preparation of this book. It also highlights the broader linkages, similarities and differences between the two areas, some of which will be explored in more detail in subsequent chapters.

3.1 Objectives

Fossil fuels (mainly coal but also natural gas and to some extent oil) provide the bulk of electricity generated in the world today, and they are projected to dominate the power sector up to 2030 (IEA 2008a) and beyond (IEA 2008b). Fossil-based electricity sources are under increasing pressure to reduce their GHG (mainly CO_2) emissions in order to mitigate climate change. This requirement has accelerated technological R&D efforts to capture CO_2 and dispose of it in geological formations.

Another important source of electricity is nuclear power. The emissions of GHGs and other air pollutants are very low even if one considers the indirect emissions arising from the construction to the decommissioning of power plants and all activities in the nuclear fuel cycle, from uranium mining to enrichment and fuel fabrication to final disposal of the RW. This last item has been a conundrum for the nuclear industry for decades but there is now a general consensus that disposal of high-level RW in suitable geological formations is the ultimate solution and that it is technically viable.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage (IPCC 2005) provided a useful synthesis of the then available knowledge from a fast evolving research field. Research and technological development related to geological disposal of RW has a somewhat longer history but no recent international synthesis has been published. Except for a few sporadic efforts dealing with selected topics, no systematic comparison has been prepared so far about the issues involved in the geological disposal of CO_2 and RW. This book intends to fill the gap by reviewing the state of the art in these two fields, preparing an in-depth comparative assessment of the similarities and differences, the already resolved issues and the remaining key challenges, and by evaluating the policy implications emerging from the comparative study.

Accordingly, the main objective of this book is to present a comparative assessment of CO_2 and RW disposal. Information from such an assessment is expected to foster future scientific research and to become a useful component of the knowledge base for policymakers when considering various options for the future energy supply in their countries or regions.

The main *scientific* objectives of the study are to explore:

- The main issues/challenges in the geological disposal of CO_2 and RW;
- The state of the art in these two fields: issues already resolved, those remaining open, unknown or uncertain;
- The common issues in and the main similarities and differences between CO_2 and RW;
- The possibilities regarding what scientists working in these two fields can learn and/or adopt from each other.

The main *policy-relevant* objectives are to examine:

- The key factors to consider in domestic decision making (especially in formulating long-term energy strategies);
- The relative benefits and drawbacks of geological disposal of CO_2 and RW;
- The issues/aspects requiring international coordination and treaties;
- The main domestic regulatory requirements for implementation.

Implementing these ambitious objectives is not a simple task. According to the experience gained from this project, the links between the two communities working on CO_2 and RW disposal, in terms of sharing knowledge and experience, are rather sparse (limited to a few special aspects) in the area of the natural sciences (e.g. geology) and the environmental and engineering sciences as well as in the social sciences (ranging from legal to economic and public acceptance issues). However, the results indicate that there are many similarities between these areas and that one can derive useful information from the differences as well.

It is important to note that utmost attention has been devoted to keeping this comparative assessment neutral and non-adversary. It is an explicit objective of this book to avoid any comparison, let alone conclusion, as to the superiority of one technology over the other. In any case, this would be a futile exercise since the numerous local and nation-specific factors will ultimately determine the relative importance, advantages and shortcomings of each technology in accordance with national energy strategy priorities.

3.2 Shared Issues, Similarities and Differences

Over its long history, mankind has been changing the environment at increasing temporal, spatial and complexity scales. Already in the nineteenth century George Perkins Marsh recorded the transformation of several components of the natural environment through human activities (Marsh 1874). Since the 1980s several publications have documented the human-induced changes in land cover and soils, the biosphere and the atmosphere (see, for example, Turner et al. 1990). Beneath the surface, deep mining has been going on for a long time and has also clearly impacted at depth (e.g. gold mines or drilling for oil and gas extending to a depth of 3,500 m). However, with the introduction of geological disposal of CO_2 and RW, humanity is entering a new phase in transforming the Earth, this time impacting on the deep underground in a different way.

Both CO_2 and RW disposal involve what might be called 'inverse geological transformation'. As opposed to traditional geological exploration that looks for underground space from which to extract material and remove what is useful, the objective in the case of disposal is to look for underground space in which to deposit something. RW research started doing this decades ago and CO_2 disposal has triggered a new upswing more recently. RW disposal will affect relatively small tracts for a very long time while CCD will spread over large expanses under the terrestrial and oceanic surface for considerably shorter periods of time, except in such cases as that of depleted oilfields, in which pressurized CO_2 could remain in place for very long time as well. This also implies a reversal of concerns at the surface regarding the hazards associated with removing material from beneath the ground surface as opposed to those associated with placing substances there.

A good understanding of geological formations and processes is a prerequisite for geological disposal of CO_2 and RW. Cross-learning between the fossil resources sector and the area of RW disposal has been going on for decades in both directions in a few very specific areas. In the exploration stage of an RW disposal site, geophysical methods and other techniques that were invented by the oil industry are used. Several organizations working on RW disposal have used the know-how of the oil and gas industry. The transfer of knowledge in the other direction is more recent. Although the main technical aspects concerning scale, risks and scope are different, the scientific advances made in RW disposal research over the past 3 decades in simulating multiphase flows and reactive transport processes in deep geological systems is valuable for research on CO_2 disposal. Various concepts, methods and tools developed in establishing the scientific foundations for RW disposal have been adopted in the geological research related to CO_2 disposal.

Looking at the geological aspects first, we find interesting similarities as well as major differences between the geological disposal of CO_2 and that of RW. Both substances require reasonable tectonic stability, and locations with at least one natural barrier against migration. The principal geological formation for CO_2 disposal is certain types of sedimentary (soft) rocks while radioactive wastes can be disposed of in hard rock as well. Both substances will trigger local effects on the geological environment as a result of the emplacement, although the nature of the effects (e.g. thermal cooling versus heating, different geochemical and geomechanical effects, etc.) differs.

Post-emplacement monitoring is usually required in both cases, although RW disposal should be passively safe and not have to rely on monitoring or any other action. Therefore, unless monitoring takes place very close to the disposal site, it is very unlikely that any releases of radioactivity will be detected for a very long time. One obvious area of joint interest is risk assessment methods: how best to evaluate long-term risks and prove the security cases. RW has a long history that CCD can learn from.

Perhaps the largest differences are related to the volume and toxicity of the waste products for disposal. Gigatonnes of fluid CO_2 will need to be injected into the disposal media whereas the volume of high-level radioactive waste accumulated so far amounts to a few hundred thousand tonnes. In contrast, the direct environmental and health hazards of CO_2 are relatively modest (except in extreme cases of seepage in valleys with human settlements), while high-level waste contains radioisotopes which emit alpha, beta, gamma and neutron radiation. External exposure to high levels of gamma radiation or neutrons is harmful and can be fatal to most species, including humans.

Another important difference is in the disposal technologies. CO_2 disposal is carried out through wells that extend to great depths and is based on oil/gas drilling techniques in terms of engineering, while for RW, mining techniques are used to create the tunnels and vaults at a depth of a few hundred metres. The latter technology uses a combination of engineered and natural barriers.

Both substances undergo long-term decay: CO_2 will be bound and absorbed by the host media through chemical processes, while the radiotoxicity of RW will decline as well. The timescales and containment period may be significantly shorter for CO_2, ranging from centuries to millennia, whereas RW may require safety assessment timescales to cover at least 10,000 and possibly as much as 100,000 or a million years. Yet the timescales for both are long enough for these to become a public liability if remediation of leakage, compensation of victims or repair and rehabilitation of the affected area is required.

Alternative solutions to underground disposal exist for both substances to reduce the time until toxicity levels or hazards are acceptable. They could be transformed into less harmful or totally harmless matter, at least partially. Partitioning and transmutation of RW would reduce its volume, radiotoxicity and the duration of the hazard. Chemical mineralization of CO_2 would immediately eliminate both atmospheric and geological hazards. However, both methods have their drawbacks.

A comparable variety of similarities and differences can be observed in the issues concerning the implementation of CO_2 and RW disposal. The timing of the disposal activity relative to the time of the waste generation has several implications. CO_2 will require disposal within a short time after it has been captured because temporary storage, albeit in principle possible, would be very expensive considering the huge volumes involved. In contrast, RW has been safely stored for decades in the past and this practice could continue for decades into the future before emplacement in a final repository. This means that CO_2 disposal will require an upfront investment in exploration, site assessment, licensing, infrastructure, equipment, etc., which will be recovered during the operation time of the disposal site through the avoided CO_2 emission costs (tax or tradable permits), while nuclear reactor operators can set aside a small fraction of their per kWh sales revenues for establishing the ultimate disposal site at a later time.

A broader economic aspect in which the management of CO_2 and RW become similar with the advent of CCD is the internalizing of the costs. This has largely been the case for RW, while CCD involves bringing home in two ways what has so far been a global externality: economically, by paying for the costs of separating CO_2 from the biogeochemical cycle and keeping it away from the atmosphere, and geographically, by keeping the waste within or relatively close to the region of its origin.

At the boundary between economics and law the question arises as to the ownership of the underground space in which these waste products will be disposed of. Some legal systems (e.g. that of the USA) grant property rights (including the right to extract resources) to the owner of the surface area. In most cases, however, the underground space is in public (government) ownership. In either case, securing the right to use this space for disposal involves contentious issues. The case of CO_2 is somewhat more complicated because it can migrate underground to large distances from the injection wells, depending on the geological formation, while RW will stay at the location of the engineered barrier system for a thousand years or longer.

Another legal issue is liability. With the introduction of the geological disposal of CO_2, the fossil power industry enters new legal terrain on account of the need to deal with the liability associated with the CO_2 disposal sites for possibly hundreds of years. The final solution for the extremely long liability period is likely to be similar in both domains: transfer of responsibility and liability to a state or government entity. The nature and magnitude of the payment by the operator of the disposal sites for the virtually infinite public liability will need to be resolved in both cases.

The lack of public acceptance or outright public opposition can prevent the implementation of any project irrespective of the actual and proven risks and benefits. Energy infrastructure, industrial sites and hazardous material are particularly exposed to the vagaries of public sentiments that can be easily manipulated by interest groups whose stakes or political agendas are at odds with the proposed project. These tendencies have long been observed for RW and are emerging for CO_2 as well. An unequivocal similarity between fossil electricity with CCD and nuclear power with RW disposal is that both are condemned and campaigned against by most environmental non-governmental organizations (NGOs).

The long struggle and many failures in various countries in earlier attempts to search for, characterize and select sites for RW repositories, and the experience from more recent and successful site selection procedures, could be a valuable source of information for those working on CO_2 disposal. The importance of openness and transparency, public information and public participation during not only site selection but all phases of decision making during RW disposal programmes cannot be overemphasized. The experience with such procedures could well be beneficial for all phases of CO_2 disposal programmes (capture facilities, transport routes, disposal sites). At this stage it is not clear what will be easier, organizing information campaigns and public dialogues to foster public acceptance at a few potential RW disposal sites or in many potentially affected communities for large-scale CO_2 disposal programmes.

A related issue is the possible link between liability, compensation and public acceptance relevant for both CO_2 and RW disposal. Willingness to accept (WTA) studies in economics indicate that people are willing to accept some level of environmental menace if they feel properly compensated. The unresolved question is whether very large compensation schemes would really increase public acceptance or not. Astronomic compensation schemes might lead to diverging public reactions. They might increase trust ('there must be a very high level of confidence that nothing will go wrong') or might undermine it ('it will be such a big disaster that no one will be left to compensate or to be compensated'). This is possibly a cultural issue that cannot be resolved in a general way.

Even if CO_2 and RW disposal are demonstrated to be safe, economically efficient (in terms of preserving the economic competitiveness of the related energy technology) and acceptable to the current generation, there are still some concerns that could be raised and should be discussed from the perspective of environmental ethics. Intergenerational equity and the concept of sustainability imply two important principles: first, the present generation should properly take care of its wastes and not leave them and the resulting burden to future generations; second, the present generation should leave all options (including technologies) open for future generations to the largest possible extent. In addition to other concerns, opposition by environmentalists against nuclear power and fossil-based electricity stems to a large extent from the alleged inability of the nuclear industry to dispose of RW safely and on the fossil fuel industry's dumping its CO_2 into the atmosphere and both thus potentially harming future generations. However, they ignore the value future generations might attach to the availability of these technological options for serving their own energy needs.

One option to be considered for reducing the risk of geological disposal in the case of both CO_2 and RW is siting disposal facilities in distant, possibly unpopulated, areas. Although long distance transport of electricity is possible, it is practical to have power plants relatively close to large population centres. This will involve transport of CO_2 and RW to the disposal sites. Transport of both substances is technically feasible. It seems to be easier and less expensive for the relatively small volume of RW to go by road, rail or sea. CO_2 will need pipelines, possibly with boosters, and this might become a more significant cost factor. Multinational (i.e. joint) disposal sites shared by small countries would make a lot of sense economically for both substances, especially for RW from countries with few nuclear reactors, high population density or an unsuitable environment for disposal, but they may prove politically impossible.

A possibly serious disturbance that might affect both CO_2 and RW disposal is 'remote infection', where remote can be just a few hundred kilometers or continents away. As examples of nuclear power accidents or, more recently, the offshore oil industry disaster in the Gulf of Mexico (spill after the explosion of a drilling platform) indicate, remote events can trigger profound changes in policy, regulation, public acceptance and other conditions anywhere in the world. Distant incidents might lead to much more stringent safety standards (irrespective of whether they are justified under the local conditions) with severe cost implications. The nuclear industry, and thus RW, has long been globalized in this respect. CO_2 disposal might be more heavily exposed to the risk of remote infections because dozens to hundreds of sites will be established and operated in a country compared to one or at most two RW disposal facilities.

Another important similarity between CO_2 and RW disposal is the prominent role of international coordination. In connection with RW disposal, the International Atomic Energy Agency (IAEA) has been supporting its Member States and the international community through scientific and technical information (IAEA 1989, 2007, 2009) and management and safety guides (IAEA 2006, 2008a, b). Work on CCD has become an increasingly important area of activity of the IEA Greenhouse Gas R&D Programme, which is an international collaborative research programme established as an Implementing Agreement under the IEA. Workshops, conferences and web-based seminars provide forums for information exchange; general and technical publications serve the CCD community (see, for example, IEA GHG 2007, 2008, 2009).

In relation to international climate change negotiations under the United Nations Framework Convention on Climate Change (UNFCCC), the two technologies seem to face the same problem. In the Marrakesh Accords (specifying the detailed rules for the implementation of the Kyoto Protocol), nuclear energy was excluded as a GHG mitigation technology eligible to earn Certified Emission Reductions (CERs) in connection with international mitigation activities like the Clean Development Mechanism (CDM) or Joint Implementation (JI). No explicit exclusion exists for CCD but it is not a recognized technology either. Negotiations texts discussed in 2009–2010 list various options regarding the role of both nuclear energy and CCD in the flexibility mechanisms, ranging from exclusion to full recognition. De Coninck (2008) presents the diversity of stakeholders' convictions about CCD that influence the outcome of the negotiations. Although scientific assessments by the IPCC (2007b) and the IEA (2008a, b) as well as others clearly demonstrate the importance of both technologies in climate change mitigation, the outcome of the negotiations concerning their inclusion in flexibility mechanisms under future protocols to the UNFCCC is difficult to predict.

4 Comparative Assessments Across Themes and Regions

This section provides a succinct overview of the chapters that follow and indicates the logic behind the order in which they are arranged. This overview is explicitly not intended to steal the thunder by presenting results of individual chapters. They are all worth reading for their own merit. It is hoped that this summary will be useful for readers by providing an overall framework and some background information about each paper.

4.1 Thematic Chapters

The first part of the book explores selected aspects of the geological disposal of CO_2 and RW. It is remarkable to note the number of disciplines that are needed to contribute towards resolving the issues associated with the various steps of the disposal process, from early site exploration to post-closure liability regulation.

The starting point for the comparative assessment across the many complex issues involved in geological disposal is geology itself. The bedrock for the whole book is the chapter by Bachu and McEwen (2011). They provide a superb overview of the issues to be taken into account when searching for appropriate geological formations for disposing of CO_2 and RW. They start with the properties of these waste materials and compare the resulting essential requirements for the geological media and the emplacement as well as the impacts of emplacement on the geological environment and the related site activities. This chapter is not only an excellent comparative study, it is also valuable for scientists working on specific issues of CO_2 or RW disposal but who would like to have a state-of-the-art overview of the broad range of relevant geological topics. The comparison table developed by the authors has served as a starting point for many regional chapters.

Once the deep geological factors have been clarified, the next step is to assess possible implications for humans and the environment near and above the surface. Numerous environmental issues arise during the operation of the disposal sites for CO_2 and RW, and after these are closed. They will need to be taken into consideration in selecting, designing, establishing and closing the sites. West et al. (2011) consider the main environmental and human health hazards, their essential features and impact mechanisms. The different properties of CO_2 and RW give rise to rather different kinds of hazards; however, the authors identify interesting similarities in the approaches to addressing the related environmental issues.

Addressing the environmental and human health risks properly requires their in-depth assessment and management. Maul (2011) explores the related methodological issues in these two fields and compares them in the context of the risk assessment process, from basic principles to analysing uncertainties by using scenarios and conceptual models. He observes that many tools developed for risk assessment in RW disposal, especially generic databases and computer models, can likewise be used for assessing the risk involved in CO_2 disposal.

In order to minimize the potential for detrimental health and environmental impacts and to support the pertinent risk management and remediation activities outlined in the chapters discussed above, extensive monitoring is required. Monitoring activities track changes in the geological media and follow the fate of the disposed material from site selection through operation to long after the closure of the disposal facilities. Brunskill and Wilson (2011) provide an overview of the applicable monitoring methods for CO_2 and RW disposal, compare their relevant aspects and provide examples of the adoption of certain methods employed in one domain for use in the other.

A major step between capturing CO_2 at the power plant or storing RW at temporary facilities and their geological disposal is transport, which can involve long distances in both cases. Gómez and Tyacke (2011) present the transport systems for transferring CO_2 and RW to the disposal site. The profound differences in the volume and key properties of these materials require completely different transport techniques (pipelines for CO_2; rail, ship or truck for RW), thus the associated safety standards also differ. Yet there are some commonalities as well: concerns about routing, the need for a clear regulatory framework and public perception of the transport-related risks, and thus the acceptance of the transport schemes, are examples of these.

Establishing the disposal sites involves rather different kinds of engineering activities for CO_2 and RW. The former involves deep-wellbore technologies with a long history of technological development in the oil and gas industry, whereas the latter can rely on an even longer history and experience in mining. Tshibangu and Descamps (2011) explore these aspects. Given the differences in the required properties of the geological media and in the volume and properties of the waste material, the comparative analysis mostly reveals obvious differences in site engineering but also finds some interesting similarities.

Suitable geological formations, reassuring risk assessment results and monitoring concepts, safe transport and site engineering schemes are all important prerequisites for geological disposal of both CO_2 and RW. Whether and to what extent it will be used also depends on the costs and the resulting competiveness of the electricity generated. Toth and Miketa (2011) present an overview of recent disposal cost estimates for CO_2 and RW and analyse the repercussions of the disposal costs on the total electricity costs. Their results indicate that the costs of RW disposal amount to a small fraction of the cost of electricity and in many countries have long been considered in the costing of nuclear power in one way or another while CO_2 disposal cost is a new element in costing fossil fuel-based electricity and, together with capture and transport, can increase the total electricity cost significantly. The alternative to CCD is continued CO_2 emission and either paying the applicable carbon tax or buying emission permits, both of which also lead to an increase in power cost.

A diverse range of legal and regulatory issues arise in the geological disposal of both CO_2 and RW. One of the major concerns, liability issues, is addressed by Wilson and Bergan (2011). The authors take case studies from several countries on managing liability for RW, on the one hand, and compare the current proposals regarding liability for CO_2 in the USA and the European Union, on the other. They present a matrix of seven liability-related questions and pertinent features of geological disposal for analysing similarities and differences between the CO_2 and RW cases. The key similarity is the following: owing to the very long time horizons (a few hundred to tens of thousands of years), industry and government will be jointly responsible for managing liability over the short term but liability will eventually be transferred to the government over the long term.

The obvious and considerable risks involved in the disposal of CO_2 and RW make public acceptance a particularly sensitive issue. In their chapter, which takes the form of a detailed overview rather than a systematic comparison, Reiner and Nuttall (2011) identify many factors that influence public perception. They take a closer look at the drivers of public acceptance related to CO_2 and RW disposal and conclude that it is difficult to separate the perception of disposal risks from the fears engendered by the images and associations of the related technologies, like power plant accidents and nuclear weapons in the case of RW.

While it is relatively easy to solicit and measure the views of the current generation, the situation is much more difficult when today's actions have implications for future generations over a very long time horizon. Brown (2011) explores the ethical principles of intergenerational equity involved in the conundrum of changing the Earth's climate by emitting CO_2 versus mitigating CO_2 emissions but leaving behind CO_2 and/or RW in geological formations. The ethical dilemmas are complicated by the state of science and the magnitude of uncertainties associated with the various options because improving knowledge and reduced uncertainties can change the ethical conclusions within the same ethical framework while the same level of knowledge and uncertainty can lead to different conclusions in different ethical frameworks.

Ethical considerations are one of the psychological factors determining people's perceptions and eventual acceptance of a technology. De Groot and Steg (2011) analyse five psychological factors driving acceptability judgements: the dreaded or unknown character of the technology in question, the related affect, the moral aspects, fairness and trust. The relative importance of these factors varies somewhat between CO_2 and RW, the latter being a better known substance but its disposal technology less known. The authors argue that reasoning and understanding play an important role; therefore it is possible to influence and improve acceptability by public information campaigns that deliver clear and objective information about the risks. However, it seems to be more difficult to overcome emotional barriers stemming from hunch-based attitudes.

4.2 Regional Chapters

We are also seeking here to learn lessons from a series of case studies that look at geological disposal of CO_2 and RW in a regional or national context. The second part of the book presents comparative assessments for selected regions. The early availability of some of the thematic chapters, particularly that on geological foundations by Bachu and McEwen (2011), was very helpful in preparing some of the regional case studies. The thematic chapters summarized above present comparative assessments in general; the regional chapters focus on region-specific issues, particularly the prevailing geological and environmental conditions relevant for CO_2 and RW disposal. They also highlight socioeconomic issues (economic, legal, public acceptance, etc.) to the extent that these aspects have already been addressed in a given country or region.

We start our world tour in North America and proceed eastward. Oldenburg and Birkholzer (2011) review the current status of CO_2 and RW disposal in the USA and Canada. Their comparative analysis surveys the targeted geological formations in this region and observes that the disposal of both CO_2 and RW is believed to be technically feasible. The authors also look at the opportunities identified and the remaining challenges within a comparative framework.

There have been long-established RW disposal programmes for decades in many Western European countries while CCD research projects emerged more recently. The European Commission supports and coordinates research in both areas. Toth et al. (2011) investigate three large countries in the region that have significant shares of both nuclear and fossil electricity in their national generation mixes: Germany, France and the UK. They focus on the comparative analyses between CO_2 and RW within the three countries and intentionally avoid the comparison of CO_2 and RW programmes across the three countries, this being beyond the scope of this book.

Several countries in Eastern Europe also rely on a combination of nuclear and fossil sources for their electricity generation. The search for RW disposal solutions has been going on for some time at varying levels of intensity in most of these countries. CCD is being increasingly considered as well because these countries are listed in Annex I of the UNFCCC (United Nations 1992), and as such they are obliged to reduce their GHG emissions, although their mitigation commitments under the Kyoto Protocol are well above their current emissions. Hódossyné Hauszmann et al. (2011) present a regional overview across eight countries in Central and Eastern Europe. Their analysis highlights the challenges that small countries are facing in the geological disposal of both CO_2 and RW.

The next country on the journey towards the east is the Russian Federation. Cherepovitsyn and Ilinsky (2011) focus on the European part of the country, where most of the population, economic activities and energy use are located. The authors observe that the disposal of RW accumulated from civilian and military nuclear programmes is an increasingly pressing task, and identify several suitable formations in the region under consideration. Since GHG emissions in the Russian Federation are also well below the Kyoto Protocol commitment, CO_2 disposal is less urgent, on account of which the authors concentrate on lucrative options like enhanced oil recovery (EOR).

As the world's largest CO_2 emitter, albeit without any legally binding mitigation commitment so far, and also a country with a very ambitious nuclear power expansion programme, China is a particularly interesting case for comparing the geological disposal of CO_2 and RW. Wang and Pang (2011) point out that currently both substances are considered as a resource in China: CO_2 for EOR, enhanced gas recovery (EGR) and enhanced coalbed methane (ECBM) recovery, and spent nuclear fuel for its uranium and plutonium content accessible by reprocessing. The search for possible disposal sites seems to follow similar patterns for both CO_2 and RW, from national screening to gradually zooming in on promising areas and then increasing the depth of the investigation. The authors compare a broad range of issues involved in geological disposal in the Chinese context.

Any underground activity creates special challenges in a region close to plate boundaries, crustal movements and the resulting active faults. The preference for tectonic stability for the disposal of both CO_2 and RW appears to be difficult to satisfy in such cases. Koide and Kusunose (2011) summarize relevant elements of the immense knowledge base accumulated in Japan about the long-term stability of the various formations and the prediction of crustal movement relevant for RW disposal as well as the impact of large-scale CO_2 disposal on the geological environment under such circumstances. They draw on an impressive diversity of studies and experiments. They present solid scientific foundations for analysing geological formations with regard to their suitability for disposal of CO_2 and RW, but they also raise a series of open questions and uncertainties due to the complex geological characteristics of the Japanese archipelago.

The next step in our journey takes us to the southern hemisphere. Surridge et al. (2011) describe the current status and future plans for the geological disposal of CO_2 and RW in South Africa. This country is characterized by the common problem of countries with only a few nuclear power plants: the small amount of RW that accumulates even over decades of operation and the high fixed costs of establishing a geological repository makes the latter economically unattractive. Nonetheless, South Africa is also exploring final disposal options while at the same time establishing safe RW storage facilities. As a developing country, it is not yet committed to reducing its GHG emissions but the CCD option is being seriously investigated because of the country's increasing reliance on its abundant and cheap coal resources for power generation and because CO_2 mitigation may be required under future global climate change agreements.

Ending our world tour by returning to the American continent, the study by Heemann et al. (2011) compares the region-specific issues of geological disposal of CO_2 and RW in two Latin American countries utilizing nuclear power in their electricity mix, namely Brazil and Argentina. Brazil is apparently blessed with huge and diverse energy resources: hydropower dominates the electricity sector, abundant uranium reserves have been identified and the CO_2 disposal potential assessed so far is also vast. A reasonably good understanding of suitable CO_2 and RW disposal options seems to be emerging in both countries.

The regional assessments indicate the availability of huge geological capacities for CO_2 disposal and also of suitable geological formations for RW disposal in several regions (North America, Latin America, South Africa, Russian Federation). This allows a great deal of flexibility in choosing the most suitable energy sources based on other important decision criteria specified for the energy strategies of these regions.

5 Concluding Remarks

Fossil fuel-based electricity and nuclear power remain two key energy supply technologies to satisfy the fast increasing energy demand under increasing GHG emissions constraints and other energy policy concerns. This book is the first attempt to provide a comprehensive comparative assessment of these two technologies, explore their relative merits and shortcomings and identify opportunities for learning and transferring experience between them.

We have shown here that there are several reasons originating in scientific research and technological development that make such a comparative assessment a meaningful and promising exercise. The value of the insights gained from evaluating the two technologies in a comparative framework is also obvious for policymakers.

The thematic chapters in this book indicate that the balance of similarities and differences as well as the mutual learning opportunities vary across the topical areas. More differences have been detected in the domains of the natural and environmental sciences like geology and environmental impacts as well as in engineering. The number of similar features is higher in the areas primarily addressed by the social sciences, like public acceptance, legal and liability issues, etc. The regional chapters demonstrate that the relative importance of these similarities and differences varies depending on the broader context and the prevailing geological, geographical and socioeconomic conditions of a given country or region.

The benefits and drawbacks of introducing/expanding nuclear power as well as of continued reliance on fossil energy sources with CO_2 capture need to be systematically assessed with a view to the geological disposal of the waste products (RW and CO_2) across a wide range of issues and against numerous criteria in order to make informed choices. Such assessments require input from a large and diverse array of scientific disciplines as well as innovative approaches to integrate the disciplinary findings for decision making. The comparative assessments presented in this book represent a first but hopefully useful step in this process.

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References

Bachu S, McEwen T (2011) Geological media and factors for the long-term emplacement and isolation of carbon dioxide and radioactive waste. In this volume

Brown DA (2011) Comparative ethical issues entailed in the geological disposal of radioactive waste and carbon dioxide in the light of climate change. In this volume

Brunskill B, Wilson M (2011) Monitoring methods used to identify the migration of carbon dioxide and radionuclides in the geosphere. In this volume

Cherepovitsyn A, Ilinsky A (2011) Comparison of the geological disposal of carbon dioxide and radioactive waste in European Russia. In this volume

de Coninck H (2008) Trojan horse or horn of plenty? Reflections on allowing CCS in the CDM. Energ Policy 36:929–936

de Groot JIM, Steg L (2011) Psychological perspectives on the geological disposal of radioactive waste and carbon dioxide. In this volume

Gómez DR, Tyacke M (2011) Transport of carbon dioxide and radioactive waste. In this volume
Heemann R, Ketzer JM, Hiromoto G, Scislewski A (2011) Assessment of the geological disposal of carbon dioxide and radioactive waste in Brazil, and some comparative aspects of their disposal in Argentina. In this volume
Hódossyné Hauszmann Z, Scholtz P, Falus Gy (2011) Carbon dioxide and radioactive waste in Central and Eastern Europe: a regional overview of geological storage and disposal potential. In this volume
IAEA (International Atomic Energy Agency) (1989) Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, vol 99, IAEA Safety. IAEA, Vienna
IAEA (International Atomic Energy Agency) (2006) Geological Disposal of Radioactive Waste, vol WS-R-4, IAEA Safety Standards. IAEA, Vienna
IAEA (International Atomic Energy Agency) (2007) IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection: 2007 edition. IAEA, Vienna
IAEA (International Atomic Energy Agency) (2008a) The Management System for the Disposal of Radioactive Waste, vol GS-G-3.4, Safety Standards. IAEA, Vienna
IAEA (International Atomic Energy Agency) (2008b) The Management System for the Processing, Handling and Storage of Radioactive Waste, vol GS-G-3.3, Safety Standards. IAEA, Vienna
IAEA (International Atomic Energy Agency) (2009) Classification of Radioactive Waste, vol GSG-1, IAEA Safety Standards. IAEA, Vienna
IEA (International Energy Agency) (2008a) World Energy Outlook 2008. OECD/IEA, Paris
IEA (International Energy Agency) (2008b) Energy Technology Perspectives 2008: Scenarios & Strategies to 2050. OECD/IEA, Paris
IEA GHG (International Energy Agency Greenhouse Gas R&D Programme) (2007) Storing CO_2 Underground. IEA Greenhouse Gas R&D Programme, Cheltenham
IEA GHG (International Energy Agency Greenhouse Gas R&D Programme) (2008) Geologic Storage of Carbon Dioxide: Staying Safely Underground. IEA Greenhouse Gas R&D Programme, Cheltenham
IEA GHG (International Energy Agency Greenhouse Gas R&D Programme) (2009) Natural and Industrial Analogues for Geological Storage of Carbon Dioxide. IEA Greenhouse Gas R&D Programme, Cheltenham
IPCC (Intergovernmental Panel on Climate Change) (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Metz B, Davidson OR, de Coninck HC, Loos M, Meyer LA (eds) Cambridge University Press, New York/Cambridge, UK
IPCC (Intergovernmental Panel on Climate Change) (2007a) Climate change 2007: synthesis report. Pachauri RK, Reisinger A (eds) Cambridge University Press, New York/Cambridge, UK
IPCC (Intergovernmental Panel on Climate Change) (2007b) Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Cambridge University Press, New York/Cambridge, UK
Koide H, Kusunose K (2011) Geological disposal of carbon dioxide and radioactive waste in the geotectonically active country of Japan. In this volume
Marsh GP (1874) The Earth as Modified by Human Action. Scribner, New York
Maul P (2011) Risk assessment, risk management and remediation for the geological disposal of radioactive waste and storage of carbon dioxide. In this volume
Oldenburg CM, Birkholzer JT (2011) Comparative assessment of status and opportunities for carbon dioxide capture and storage and radioactive waste disposal in North America. In this volume
Reiner DM, Nuttall WJ (2011) Public acceptance of geological disposal of carbon dioxide and radioactive waste: similarities and differences. In this volume
Surridge AD, Cloete M, Lloyd PJ (2011) The geological storage of carbon dioxide and disposal of nuclear waste in South Africa. In this volume
Toth FL, Miketa A (2011) The costs of the geological disposal of carbon dioxide and radioactive waste. In this volume
Toth FL, Roehrl RA, Miketa A, Barkatullah N (2011) Comparing the geological disposal of carbon dioxide and radioactive waste in Western Europe. In this volume

Tshibangu KJ-P, Descamps F (2011) Engineering challenges in the geological disposal of radioactive waste and carbon dioxide. In this volume

Turner BL II, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB (eds) (1990) The Earth as Transformed by Human Action: Global and Regional Change in the Biosphere over the Past 300 Years. Cambridge University Press, New York

UN DESA (United Nations Department of Economic and Social Affairs, Population Division) (2009) World population prospects: the 2008 revision. http://esa.un.org/unpd/wpp2008/peps_documents.htm

UNDP (United Nations Development Programme) (2005) Energizing the Millennium Development Goals: A Guide to Energy's Role in Reducing Poverty. UNDP, New York

United Nations (1992) United Nations Framework Convention on Climate Change. United Nations, New York

Wang J, Pang Z (2011) Comparison between geological disposal of carbon dioxide and radioactive waste in China. In this volume

West JM, Shaw RP, Pearce JM (2011) Environmental issues in the geological disposal of carbon dioxide and radioactive waste. In this volume

Wilson EJ, Bergan S (2011) Managing liability: comparing radioactive waste disposal and carbon dioxide storage. In this volume

World Bank (2009a) Global Development Finance: Charting a Global Recovery, vol I, Review, analysis, and outlook. The World Bank, Washington, DC

World Bank (2009b) Global Economic Prospects 2009: Commodities at the Crossroads. The World Bank, Washington, DC