Comparing the Geological Disposal of Carbon Dioxide and Radioactive Waste in Western Europe

Ferenc L. Toth, Richard A. Roehrl, Asami Miketa, and Nadira Barkatullah

Abstract The current status of and prospects for the geological disposal of carbon dioxide (CO_2) and radioactive waste (RW) are assessed for Western Europe by focusing on three large countries: Germany, France and the UK. The relative importance of the associated electricity generation technologies (coal-based and nuclear generation) varies across countries but extensive efforts are under way to explore the feasibility of and available capacities for disposing of the resulting waste. Suitable geological formations seem to be available for both CO_2 and RW disposal in all three of these countries. The main thrust of the disposal for both waste products is on national solutions despite many research projects coordinated by the European Union, and economic and energy collaboration. Research into RW disposal has a much longer history than CO_2 disposal. Yet there are learning opportunities in many areas, ranging from geology and risk assessment to regulation and liability, as well as in public information and participation in decision making, particularly with regard to site selection. Despite well-established (RW) and emerging (CO_2) European Union and international standards and regulatory principles, there are marked differences in the disposal strategies for CO_2 and RW in the three countries.

Keywords Carbon dioxide • Radioactive waste • Geological disposal • Geological formations • Disposal capacity • Western Europe • Germany • France • UK

1 Introduction

Despite declining energy intensities of economies and decreasing carbon intensities of energy systems, greenhouse gas (GHG) emissions have been steadily increasing in most countries of Western Europe. These trends seem to be difficult to reverse, despite the region's aspiration to become the global leader in climate protection and the

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policies and instruments to foster compliance with the commitments under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). Additional and more drastic measures will be required to reduce GHG emissions according to the pledges made in preparation for the 15th Conference of the Parties to the UNFCCC (EC 2009). This chapter explores in a comparative framework the implications of two key strategies currently being considered in many Western European countries to reduce energy-related carbon dioxide (CO_2) emissions: the increased use of nuclear power and CO_2 capture from fossil fuel combustion, both resulting in the need to dispose of the waste products in suitable geological formations.

For the purposes of this chapter, Western Europe is delineated so as to include all member states of the European Union (EU) as of 1993 (EU15) plus Cyprus, Iceland, Malta, Norway, Switzerland, and other small countries of the region. Western Europe has a large population, GDP and energy densities per unit of area. Although it is geographically small in comparison with other main world regions, the relative importance of different energy sources varies widely across countries. This results in substantial disparities in energy-related environmental problems, particularly in GHG emissions. Given the mandate of this chapter, we focus here on CO_2 emissions from the power sector.

Figure 1 presents the CO_2 intensities and the shares of non-fossil sources in power generation for selected countries of the region. Countries well endowed with hydropower sources (e.g. Austria, Norway, Sweden, Switzerland) can secure significant shares of their electricity requirements from this low-carbon source. Some of them (Sweden and Switzerland) complement hydropower with nuclear electricity while others (Belgium, France) generate large shares of their power from nuclear. Several countries still use huge quantities of coal and will need to find ways to reduce CO_2 emissions under the increasingly stringent EU restrictions on GHG emissions.

As a result, research on various aspects of geological disposal for the two main waste products, CO_2 and radioactive waste (RW), and the search for suitable disposal sites are pursued intently in most countries. This chapter presents lessons from comparative assessments for three large countries in the Western European region: Germany (Sect. 2), France (Sect. 3) and the UK (Sect. 4). Each section presents an overview of the current status and the main issues of the geological disposal of CO_2, followed by a similar status review for RW. This material is then used as the foundation for the three national comparative assessments. The closing section summarizes the main lessons learned.

2 Germany

2.1 CO_2 Sources and Geological Disposal in Germany: Status and Issues

This section provides a brief overview of the most salient large-point CO_2 sources and geological disposal options that are being explored in Germany.

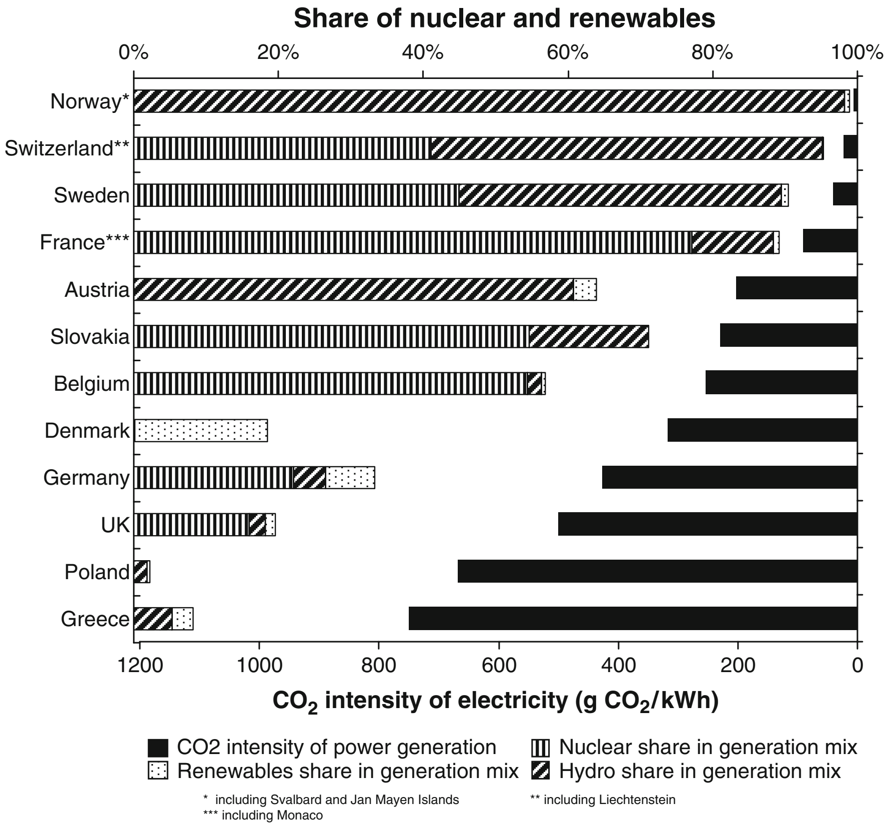

Fig. 1 CO_2 intensity and the shares of non-fossil sources in the electricity sector of selected countries (Source: IAEA calculations based on IEA (2008a) data)

2.1.1 Fossil-Based Electricity and CO_2 Emissions

In 2007, CO_2 emissions in Germany were 824.2 million tonnes (Mt) or roughly one-fifth of EU27 emissions (UBA 2009a; EEA 2008). Total energy-related CO_2 emissions were estimated at 755.3 Mt, of which 51% originated from the energy industries (385.5 Mt). Public electricity and heat production accounted for 345.7 Mt CO_2 of which 291.1 Mt originated from solid fuels (coal, lignite), 40.7 Mt from gaseous fuels (natural gas and other gases), 3.6 Mt from liquid fuels, 10.4 Mt from biomass and 10.3 Mt from other fuels (UBA 2009a). In other words, 84% of emissions from public electricity and heat production originated from coal and lignite power plants and 12% from gas-based power plants. These large stationary sources are particularly suitable for CO_2 capture and disposal (CCD).

By 2007, net CO_2 emissions in Germany had decreased by 18.2% from their 1990 level, according to the Federal Environment Agency (UBA) (UBA 2009a), and per capita emission levels are now similar to the 1950s levels (Marland et al. 2009).

Germany's GHG emissions in 2008 were down by 23.3% relative to 1990; thus it appears that Germany has already reached its 21% reduction target under the Kyoto Protocol and the EU burden-sharing agreement (UBA 2009b).

In 2007 the Government announced an eight-point plan to reduce GHG emissions by 40% from 1990 to 2020, corresponding to an additional reduction of 270 Mt CO_2-equivalent from the 2007 level. While the plan does not include CCD, the Government has recognized the need to explore this option, as evidenced by the number of ongoing pilot studies and applications. The Government also announced the need to reach GHG emission reductions of 80% by 2050, an ambitious target that will require the consideration of all possible options, including CCD. It should be noted that in 2006 the UBA issued a position paper that examined the disposal potential and the environmental impacts of CCD and concluded that CCD was only an interim solution and would not be available for large-scale power plants in Germany before 2020 (UBA 2006).

There are considerable coal reserves and resources in Germany. The estimated lignite reserves (40,818 Mt) and resources (36,760 Mt) are some of the largest in the world and could serve current German consumption levels for another 430 years. Hard coal resources (82,947 Mt) would not run out for centuries. However, in 2007 hard coal reserves were estimated at 118 Mt which was equivalent to only 5 years of production. Estimated natural gas reserves and resources were relatively small (418 giga m^3 (Gm^3)) compared to consumption (96 Gm^3), and oil reserves and resources were relatively negligible (57 Mt), as reported by the Federal Institute for Geosciences and Natural Resources (BGR) (BGR 2008). Thus Germany has become increasingly dependent on the import of fossil fuels. Almost all the oil (97%), most of the natural gas (82%) and two thirds of the hard coal consumed in Germany was imported in 2007. Ten years earlier, only one third of hard coal was imported. In contrast, almost all lignite was produced domestically in 2008 (BGR 2008).

Coal resources are concentrated in the Rhineland in West Germany. The Tagebau Garzweiler mine near Düsseldorf is the largest lignite surface mine in the world and produces more than one quarter of the fuel for Germany's electricity. Other large coal mines are located at Heimbach and Inden close to the border with the Netherlands. Natural gas fields located in the north-western German Basin, the Upper Rhine Graben and the Molasse Basin spread over 41% of German territory. Currently, Germany's natural gas refining and production occurs mostly in the north-western state of Niedersachsen, but the country also has sizeable natural gas reserves in the North Sea. The country's largest oil producing field, Mittelplate, is located off the western coast of the North German state of Schleswig-Holstein.

In 2007 electricity use in Germany was more than 1,525 petawatt-hour, with a mix of hard coal (24.5%), lignite (27.0%), gas (12.6%), hydro and wind (4.2%), nuclear (27.9%), and oil and other solids (2.4%) (AGEB 2009). While overall coal use has decreased in recent years, more than half of electricity is still derived from coal and lignite. In view of the need for baseload power, together with the nuclear power phase-out decision and the high oil and natural gas prices over the last years, two dozen coal plants are currently in the planning or construction stage in Germany. In fact, the Federal Ministry for the Environment, Nature Conservation and Nuclear

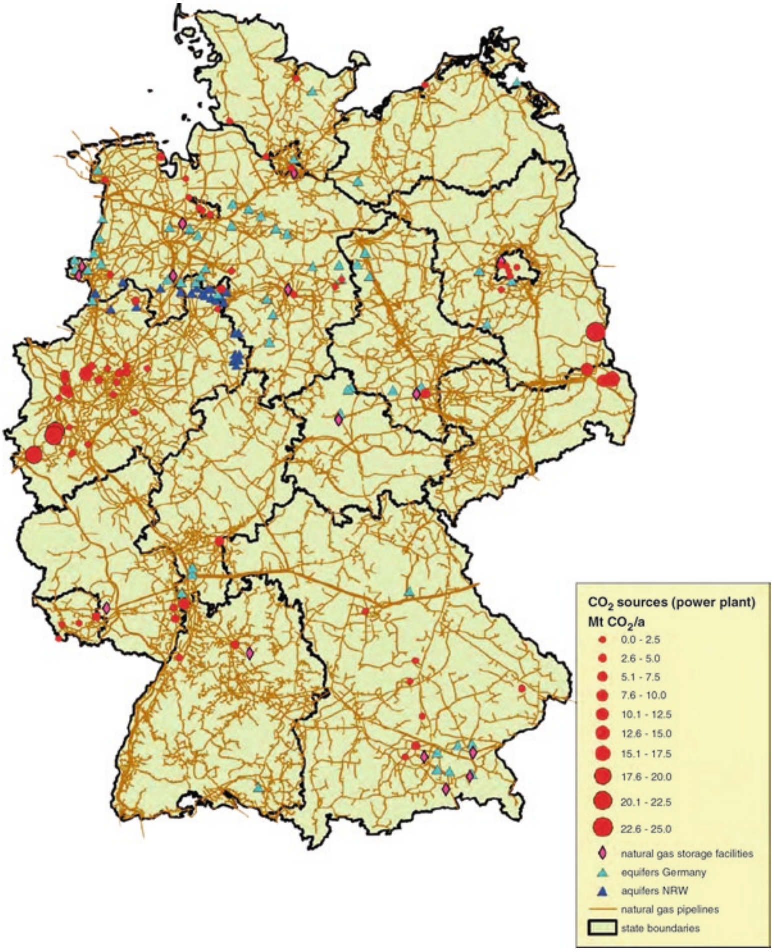

Fig. 2 Major stationary sources of CO_2 (*power plants*), potential disposal in saline aquifers and natural gas storage facilities, and the existing gas pipeline network in Germany (Source: Fischedick et al. 2007) (*see* Colour Plates)

Safety (BMU) projects a continued reliance on coal for electricity production over the next decades. Therefore CCD is expected to play an important role in CO_2 mitigation strategies in the future.

Figure 2 shows the locations of major stationary sources of CO_2 emissions (red circles) which are mainly coal power plants and some gas-based power plants. Such plants are located close to major coal mines and/or consumption centres (cities). For example, the Schwarze Pumpe power plant in the Ruhr is the largest lignite power plant in Germany, with a capacity of 2 GW and more than 10 Mt CO_2 emissions per year (Kreft et al. 2007). Figure 2 also indicates the locations of suitable geological formations for CO_2 disposal, as well as the existing gas pipelines.

The GeoCapacity project developed a geographical information system (GIS) mapping tool for the analysis of sources, potential sinks and CO_2 transport scenarios (Fischedick et al. 2007).

2.1.2 Geological Formations for CO_2 Disposal

In Germany a wide range of geological formations are being explored for CO_2 disposal (Stroink 2006). Most disposal options are based on the permeability of high-porosity geological formations. In particular, deep saline aquifers, depleted oil- and gasfields and deep (presently unexploitable) coal seams are considered to be promising options. Based on Herzog et al. (1997), Gerling (2004), Ziesing (2006) and May et al. (2003), Fischedick et al. (2007) carried out an assessment of the pros and cons of the options and found closed coal mines and salt caverns (which had also been considered) to be unsuitable. In addition to the full range of CO_2 disposal options in deep geological formations, disposal options in the sea and in biomass have also been explored. However, the marine options (in the German seabed) were considered too risky and are no longer being pursued (Stroink 2006). An increasing number of R&D activities on CO_2 disposal have been carried out in Germany, especially since the start of the EU Emissions Trading Scheme in 2005 (Krooss and May 2006). Many of these R&D activities involve partnerships between academia, government and the private sector. The main research findings are summarized below for each geological formation under consideration in Germany.

Deep saline aquifers have been identified as the option with the largest disposal capacity in Germany, with estimates ranging from 12 to 28 gigatonnes of CO_2 (Gt CO_2) (May et al. 2005; Fischedick et al. 2007). Earlier estimates were even higher, of the order of 23–43 Gt (see Bentham and Kirby (2005), based on results of the project on Geological Storage of CO_2 from Combustion of Fossil Fuel (GESTCO) (Christensen and Holloway 2004)), and 33 Gt (Kuckshinrichs et al. 2004). In fact, saline aquifers in Germany have the largest capacities in Europe, according to the Federal Ministry of Economics and Technology (BMWi 2009). However, significant research efforts will be needed to refine estimates and better assess the storage quality and potential of this option in Germany. Moreover, the risks of leakage from the geological formation (and from pipelines) require more research. Suitable saline aquifers are being explored at depths of roughly 1 km. While the option is, in principle, technologically feasible, the costs of this disposal option are expected to be relatively high (Fischedick et al. 2007). The possibility of long-term fixation of the CO_2 in the form of solid carbonate is being explored, but more research will be needed into the corresponding chemical reaction rates and the optimal mineral composition of the aquifers to support the formation of carbonates (Fischedick et al. 2007). Potential future conflicts with the use of geothermal energy (hydrothermal/hot-dry-rock approaches) and with the use of deep aquifers for seasonal energy storage have also been noted.

Depleted gasfields are the most promising option for CO_2 disposal in Germany in terms of economics and technical feasibility. These are mainly located in the North and Middle German Sedimentary Basin in Permian and Triassic sandstones (Stroink 2004).

CO_2 is stored in liquid supercritical phase. Depleted gasfields appear to be the cheapest options for geological disposal of CO_2. This is because of the use of CO_2 injection for enhanced gas recovery (EGR), and because existing gas infrastructure and technology can be used with relatively few modifications. Key technical challenges relate to the development of new materials (different types of cement and steel), and simulation and monitoring. However, conflict of use may arise in the future because of CO_2 contamination of the remaining natural gas (Fischedick et al. 2007). The estimated CO_2 storage capacity in depleted gasfields in Germany is 1.77–2.56 Gt CO_2, which is small compared to the annual emissions of almost 0.4 Gt CO_2 from large (>0.1 Mt) stationary sources (Fischedick et al. 2007). In fact, there are only 66 gasfields of adequate size in Germany to store CO_2 (Stroink 2006). An average German gasfield would be large enough to hold roughly 3–5 years of the CO_2 emissions from a typical German large lignite power plant, which emits roughly 8–10 Mt CO_2/year (BMWi 2009).

The CO_2 disposal capacity in *depleted oilfields* in North and East Germany is very limited, being estimated at less than 0.11 Gt CO_2. Proven technologies exist, and it is expected to be a low-cost option in view of the extensive experience with enhanced oil recovery (EOR). Similar to the disposal option in depleted gasfields, leakage and materials issues need to be addressed (Fischedick et al. 2007).

Deep and presently unexploitable coal seams appear to be a promising CO_2 disposal option for Germany because of the large coal resources in close proximity to coal power plants, the economic benefits of enhanced coalbed methane (ECBM) recovery. However, much greater R&D efforts will be needed, especially into the physico-chemical properties of coal under in situ conditions. The adsorption potential for CO_2 depends on the type of coal and depth. The adsorption method requires depths of roughly 1.5 km. CO_2 disposal in coal seams may make future recovery of such coal resources difficult or impossible. It will also be important to fully capture all the resulting coalbed methane, which is also a GHG (Fischedick et al. 2007). While the estimated technical potential for CO_2 disposal in deep coal seams in Germany is up to 3.7–16.7 Gt CO_2 in the regions of Münsterland and the Saar-Nahe Basin, the economic potential is probably much lower. Industrial pilot projects already exist, for example, with German participation in a project in Katowice, Poland.

CO_2 disposal in *closed coal mines* appears to be an attractive option, as these mines are located in close proximity to major CO_2 sources. However, very high safety risks have been noted, due to connections between mines that are closed and those in use, and because some mines, especially in the densely populated Ruhr, are only a few metres below the surface. There is also a conflict of use with mine gas. The estimated storage capacity is 0.7 Gt CO_2, or 15% of the mined coal seams, most of which are located in the Ruhr und Saar region (Fischedick et al. 2007).

Salt caverns suitable for CO_2 disposal exist mainly in the states of Sachsen-Anhalt and Thüringen. The estimated storage potential is only 0.03 Gt CO_2 in Germany, even smaller than in oilfields. The disposal technology exists. Safety is a major issue because of flooding with water, as well as negative experience of explosive leakage of natural gas stored in salt caverns. Salt caverns are preferred geological formations for the disposal of highly toxic waste and RW, and even the storage of documents in salt caverns for the purposes of data security is being explored in

Germany. In view of the small volumes of suitable salt caverns, such conflict of use is being taken seriously (Fischedick et al. 2007).

2.1.3 Locations and Capacity Estimates

German participation in R&D on geological disposal of CO_2 has been carried out mainly through EU research projects together with foreign partners. These projects include Joule II, GESTCO, GeoCapacity, NASCENT, RECOPOL, CASTOR, CO_2SINK, CO_2STORE, CO_2GeoNet, ICBM and Dynamis. Noteworthy national research projects on CO_2 disposal include the programme GEOTECHNOLOGIEN with ten projects (14 research institutions and 15 companies), as well as CSEGR and the Speicherkataster. It should be noted that government support for R&D on CO_2 subsurface disposal has been relatively small, particularly given the German Government's focus on renewable technologies (Krooss and May 2006).

A sandstone aquifer near the town of Ketzin (west of Berlin) is the location of a field trial of CO_2 injection and disposal. The disposal site is situated at the flank of an anticline above a salt pillow at a depth of 1,500–2,000 m. The saline aquifer formation for CO_2 injection is a Stuttgart Formation of Triassic age at a depth of 650 m. It has a thickness of up to 80 m and a Triassic Weser Formation as top seal (Förster et al. 2008). The overburden of the storage formation contains several aquifers and aquitards, including an abandoned gas storage facility. Since April 2004 preparations and measurements have been performed within the framework of the EU project CO_2SINK, including flow experiments with water and CO_2 in various sandstone types. In 2004 a seismic survey provided 3-D information of the formation. The research showed the caprocks at the Ketzin site to have good sealing properties. The CO_2 injection started in June 2008, and by April 2009, 13,077 t CO_2 had been injected (CO_2SINK 2009). It is planned to inject at least 60,000 t CO_2 over a period of 2 years (Förster et al. 2008).

Another noteworthy field trial of CO_2 injection and storage is taking place in the Altmark natural gas field, which is Europe's second largest natural gas field. The field is located in the Altmark region in the state of Sachsen-Anhalt in north-eastern Germany, roughly 120 km south–east of Hamburg, Germany's second largest city. In geological terms, the Altmark is part of the North German Basin and part of the Mid-European Basin. It contains several sub-reservoirs (Rebscher et al. 2006). The reservoir rocks are located at a depth of 3.5 km and are formed of red sandstone and siltstone with shale layers, with a wide range of porosity and permeability. Above the reservoir, there is a several hundred metre thick Zechstein salt bedrock with very low permeability which forms an effective caprock. The CO_2 injection and storage project is part of an EGR project. CO_2 has been injected in the depleted Altmark natural gas reservoirs to test their technical feasibility for EGR. The storage capacity is estimated at up to 508 Mt or roughly one fifth of the total storage potential of German gasfields. It is the only depleted gasfield available in Germany that can store the entire lifetime CO_2 emissions of a large coal power plant. Carbon capture plants are being built at the nearby Schwarze Pumpe power plant, and small 250–350 MW units are planned by Vattenfall (Vattenfall 2009).

In the CO_2STORE project, a field trial is being carried out in a saline aquifer below the village of Schweinrich, roughly 100 km north–west of Berlin and 250 km north–west of the Schwarze Pumpe power plant. The Schweinrich structure follows an elongated anticline which covers almost 100 km^2. The reservoir formations are within the Lower Jurassic and Uppermost Triassic, and are located between two large salt diapirs at a depth of roughly 1,500–1,600 m. The reservoir is about 150 m thick and consists of several layers of fine-grained, highly porous sandstones overlaid with thick Jurassic clay formations. The storage capacity is estimated to be at least 400 Mt CO_2 (Kreft et al. 2007; CO2STORE 2009).

In the NASCENT project, the BGR and its partners carried out a series of geological studies and soil gas surveys at Oechsen in the Vorderrhön region of Central Germany. In that region, natural CO_2 occurs below and within Permian Zechstein salts and was previously produced commercially (Krooss and May 2006). As part of the GESTCO project, two case studies were selected for numerical simulations of CO_2 injection, the Buntsandstein aquifer near a planned power plant at Lubmin and the abandoned natural gas field Alfeld-Elze. Another site at Kalle was also analysed (Krooss and May 2006).

The total geological disposal potential for CO_2 in Germany is estimated at 19–48 Gt CO_2, which is of the order of 30–60 years of CO_2 emissions from all large stationary CO_2 sources in the country (based on 2007 emissions) (Fischedick et al. 2007). The alternative estimate of the BGR is similar: 20 ± 8 Gt CO_2 (BGR 2009). These are estimates of the technical potentials, only a fraction of which may become economically feasible. Generally, the CO_2 disposal potential is relatively large in the north of Germany and relatively small in the middle and south of the country, compared to current German CO_2 emissions.

A study commissioned by the BMU and carried out by several research organizations assessed the storage potentials for Germany against ecological and techno-economic criteria. The study concluded that only deep saline aquifers, depleted gasfields and deep coal seams were of practical relevance for CO_2 disposal. Table 1 provides an overview of key results in terms of capacity, long-term stability, costs, state of respective technology, utilization conflicts and general risks (Fischedick et al. 2007).

Fischedick et al. (2007) combined their German capacity estimates (based on, for example, Hendriks et al. 2004) with cost estimates for Western Europe from the earlier GESTCO report to create cumulative capacity–cost curves for deep saline aquifers, depleted gasfields and deep coal seams in Germany. The authors find that 2.56 Gt CO_2 could be stored for roughly 6.5 €/t in depleted gas fields, 12–28 Gt CO_2 for roughly 8 €/t in saline aquifers, and 3.7–16.7 Gt CO_2 for roughly 13 €/t in deep coal seams. However, large uncertainties remain regarding both costs and capacities. Cost estimates were derived from German case studies and range widely, especially for CO_2 transport and disposal in saline aquifers.

2.1.4 Implementation Issues

In addition to the techno-economic issues mentioned above, a range of political, social and institutional issues will determine the overall feasibility of carbon

Table 1 Assessment of geological disposal options

Type of disposal	CO_2 storage capacity (Gt)	Long-term stability	Costs	State of technology	Utilization conflicts	General risks
Depleted gasfields	2.3–2.5	Good	Good	Very good	May be resolvable	Good
Deep saline aquifers	12–28	Good	Very problematic	Good	May be resolvable	Good
Deep coal seam	3.7–16.7	Good	Very problematic	May be resolvable	May be resolvable	May be resolvable
Depleted oilfields	0.11	Good	Very good	Very good	May be resolvable	Good
Salt cavern	0.04	Very problematic	n.a.	Good	Very problematic	Very problematic
Disused coal mine	0.78	Very problematic	Very problematic	Very problematic	Very problematic	May be resolvable

Sources: Fischedick et al. 2007; May et al. 2005 disposal options in Germany. A 2006 survey conducted by the University of Marburg showed that 93% of Germans considered climate change an important issue and that most people living close to power plants welcomed CCD. Rostock (2008) also reviewed public acceptance of CCD in Germany. While identifying public resistance as the biggest argument against this technology, especially with regard to the perceived risks during transport and disposal, he noted that the public was not yet debating the pros and cons of CCD. Whereas experts and industry representatives were generally optimistic, environmental organizations were either generally uneasy with or outright opposed to CCD. Hansson and Bryngelsson (2009) recently carried out interviews with CCD experts and reported a discrepancy between the uncertainties and the experts' optimism.

German environmental organizations have increasingly warned about the risks of CCD and its negative implications in terms of energy demand and coal lock-in. In particular, the concern has been voiced that CCD may delay efforts to move towards renewable, low-emission technologies. For example, the World Wide Fund for Nature (WWF) has generally welcomed the development of CCD, but warns against fossil lock-in, lack of transparency and potential environmental consequences (WWF 2009). At a more extreme end of the spectrum, Greenpeace Germany strictly opposes CCD and uses language identical to that in its battle against nuclear waste transport and disposal, namely 'CO_2 repository time bomb' (*Zeitbombe CO_2 Endlager*) (Greenpeace 2009).

Prominent German research institutions have focused on techno-economic assessments of CCD, typically without reference to the potential socio-political limits in Germany. For example, the Potsdam Institute for Climate Impact Research (PIK) calls for as many as 12 CCD demonstration projects to be carried out before 2015, which should demonstrate all the steps: from CO_2 capture, through transport, to sequestration, and which should also demonstrate leakage of below 0.01% per year. PIK also suggests mandating operators to buy CCD bonds for each unit of CO_2 sequestered that would be held by a state authority and handed back only after 30 years (Helda and Edenhofer 2009). According to the Öko-Institut e.V. (Matthes et al. 2009), CCD, together with renewable energy, energy efficiency and combined heat and power, can play an important role in addressing anthropogenic climate change.

The Sustainability Council (Nachhaltigkeitsrat) of the Federal Government views CCD as a necessary technology to support a transition to renewable energy, while the German Advisory Council on the Environment (Der Sachverständigenrat für Umweltfragen) has expressed its concern that CCD may become available too late and turn out to be too expensive. The German Advisory Council on Global Change (Wissenschaftliche Beirat der Bundesregierung Globale Umweltveränderung) has advised against CO_2 disposal in the sea and argued that safe disposal would need to be provided for more than 1,000 years. The UBA itself considers CO_2 capture and disposal as an interim solution at best (UBA 2006). In contrast, German industry associations are very optimistic about CCD. The German Lignite Association (DEBRIV) recommends the use of CCD, while the Hard Coal Association (GVSt) categorizes CCD as a long-term option and focuses on the further increase in power plant efficiency.

The legal basis for CO_2 disposal remains unclear. In fact, elements of the mining act (Bundesberggesetz BBergG), the recycling and waste act (Kreislaufwirtschafts- und Abfallgesetz KrW/AbfG), and the federal water act (Wasserhaushaltsgesetz) apply. On 1 April 2009 the Federal Government adopted a CCD act (Gesetz zur Regelung von Abscheidung, Transport und dauerhafter Speicherung von Kohlendioxid) that sets basic parameters and limits the liability of private operators to 30 years after the CO_2 disposal site is closed, after which the state takes over responsibility (BMU 2009). However, in June 2009 the act failed to be passed by the national parliament. It should be noted that the German CCD act is rather general and leaves a number of key questions open. The Government plans to carry out an evaluation and impact report in the year 2015 based on experience gained with CO_2 disposal from the three German pilot plants in Hürth (Nordrhein-Westfalen), Jänschwalde (Brandenburg) and Wilhelmshaven (Niedersachsen).

The BGR is developing standards and criteria for CO_2 disposal sites. To date, two relevant DIN (standing for Deutsches Institut für Normung (German Institute for Standardization)) standards exist. DIN EN 1918-1 (Untertagespeicherung von Gas in Aquiferen) provides functional and safety recommendations for design, construction, commissioning, operation, maintenance and surveillance of underground gas storage in aquifers, and DIN EN 1918-2 (Untertagespeicherung von Gas in Öl-/Gasfeldern) describes procedures and practices which are safe and environmentally acceptable, covering the subsurface aspects of design, construction, testing, commissioning, operation and maintenance of underground storage facilities in oil- and gasfields.

The German CCD act has been heavily criticized by environmental organizations, such as Greenpeace and WWF. Among other things, they have criticized the characterization of CO_2 as an economic good rather than as waste, which has important legal implications. For example, there are legal restrictions on the transport of waste, especially across national borders.

2.2 *Sources of Radioactive Waste and Geological Disposal in Germany: Status and Issues*

This section provides a brief overview of the generation and geological disposal options for RW in Germany.

2.2.1 Nuclear Installations and Waste Generation

Nuclear power has been an important source of baseload electricity in Germany since the 1970s. Thirty-one per cent of electricity had been generated by 19 nuclear reactors by the end of the 1990s. However, the Government took a nuclear phase-out decision in 2000. An agreement between the Government and nuclear power plant (NPP) operators mandated early decommissioning of reactors (after 32 years of operation). The two oldest reactors were shut down in 2003 and 2005, but the

Fig. 3 Nuclear power plants and storage facilities in Germany (Source: Sailer 2008) (*see* Colour Plates)

phase-out law was revised in 2010 and now the phase-out is expected to be completed by 2036. In 2008, 17 nuclear reactors were being operated at 12 different sites (see Fig. 3) in Germany (Sailer 2008) with a capacity of 21.5 GWe (BMWi 2009). In 2007, 27.9% of electricity in Germany was produced by NPPs (AGEB 2009), which provided 45% of the national baseload. Nuclear power is the second cheapest method of electricity generation in Germany after lignite, and much cheaper than hard coal, hydro or renewables (BMWi 2009).

Uranium is supplied primarily from Canada, Australia and the Russian Federation, and imports amount to 3,800 t/U/year. The construction of a nuclear fuel reprocessing facility at Wackersdorf was stopped amidst widespread public protests in 1989, after which German nuclear fuel was reprocessed mainly in France at the La Hague facility (86%) and to a lesser extent at Sellafield, UK, and at other locations. A smaller reprocessing facility was operated in Karlsruhe until 1990. Since 2005, transport of fuel from German NPPs to reprocessing facilities is prohibited by law (according to a revision of the 1959 Atomic Energy Act) and transport from these facilities is limited. Thus, interim storage and eventual final geological disposal have been the only remaining options since 2005.

In addition to the international classification into high-, medium- and low-level RW, Germany distinguishes between heat-generating waste (HGW) and negligible heat-generating waste (NHGW) (Sailer 2008). NHGW is basically defined as waste that will be disposed of in the Konrad repository, i.e. according to the Konrad waste acceptance requirements (Brennecke 1995; Bund 1989). In practice, HGW is more or less the same as high-level waste (HLW) according to the respective international classification (IAEA 1994). Most of Germany's HLW is kept in reactor pools and at dry interim storage facilities. By the end of 2005, 11,810 tonnes of heavy metal (tHM) of HGW in terms of spent fuel (SF) had been produced by nuclear reactors, of which 5,140 tHM had been stored in Germany and 6,670 tHM had been shipped for reprocessing (Alter et al. 2006) (see Table 2). This corresponds roughly to a volume of 14,000 m^3. Another 1,859 m^3 of HGW were produced from other sources.

In Germany, the utility companies are responsible for interim storage of SF, and they have formed joint companies to build and operate off-site surface facilities. By the end of 2007, 118,124 m^3 of NHGW had been stored at the 12 NPP sites, according to the Federal Office for Radiation Protection (BfS) (BfS 2008), at interim storage facilities in Greifswald, Jülich, Karlsruhe, Mitterteich and Gorleben (see Fig. 3), as well as at state facilities for RW from nuclear applications in research and the health, food and industrial sectors (Table 2). Sailer (2008) estimates the amount of low-level waste (LLW) and intermediate-level waste (ILW) at 100,000 m^3. Another 36,753 m^3 of NHGW had been disposed of in the Morsleben repository and 47,000 m^3 in the Asse research mine (Table 2).

Seventeen experimental and commercial reactors have been shut down and are being decommissioned, including all the reactors in former East Germany after reunification in 1990, producing roughly 10,000 m^3 of RW (WNA 2009a). Decommissioning of all reactors that are currently operating in Germany may produce an estimated 115,000 m^3 of RW (WNA 2009a).

The cumulative amount of NHGW is expected to increase to 277,000 m^3 by 2040 (see Table 3), according to the year 2000 phase-out law, i.e. a maximum lifetime of NPPs of 32 years (BfS 2008). This is based on an average 60 m^3 of NHGW produced per reactor per year. More recently BfS (2008) quotes lower estimates of 45 m^3 per reactor and year and 5,000 m^3 per reactor for decommissioning. Witherspoon and Bodvarsson (2006) report a somewhat higher estimate of 297,000 m^3 of NHGW by 2040 (see Table 3). Roughly two thirds of this amount is expected to originate from the public sector, one third from electricity utilities and the nuclear industry (NEA 2006). Energiewerke Nord (EWN) explored waste minimization strategies for electric utilities which would lead to significantly lower NHGW amounts of 192,000 m^3 by 2040, also assuming mandated 32 year maximum licences (Table 3). Waste optimization for public institutions (e.g. research, medicine and the reprocessing facility in Karlsruhe) may prove more difficult. Thus, in this scenario only 45% of NHGW would originate from electric utilities and the nuclear industry.

In 2005 the 17 operating NPPs in Germany produced 417 tHM of SF, leading to cumulative total production of 11,810 tHM by the end of 2005 (Alter et al. 2006).

Table 2 Inventory of radioactive waste in Germany, as of 31 December 2007

		Untreated waste	Interim products	Conditioned waste	Total radioactive waste	Conditioned waste added in 2007	Waste disposed of in geological repositories
Negligible heat generation waste		18,506	8,541	91,077	118,124	2,383	36,753 (Morsleben) 47,000 (Asse)
Heat-generating waste	Without spent fuel[a]	63	1,252	544	1,859	0	0
	Spent fuel from reactors	n.a.	n.a.	n.a.	(~14,000 m^3) 11,810 tHM produced[b]	n.a.	0

Sources: BfS 2008; Alter et al. 2006; and authors' estimates

[a] But including spent fuel from a thorium high-temperature reactor

[b] By the end of 2005

The cumulative amount of SF is expected to increase to 17,200 tHM or roughly 29,000 m^3 by 2040 (BfS 2008). This amount includes 20,600 m^3 of SF elements in pollux containers; 3,400 m^3 of waste conditioning facility components; 660 m^3 of vitrified HLW; 1,340 m^3 of medium-active vitrified waste from reprocessing plants; 130 m^3 from research reactors; and 2,000 m^3 from an experimental reactor and a thorium high-temperature reactor (BfS 2008). Sailer (2008) reports lower estimates of 22,000 m^3 of HGW in 2040.

The cumulative amount of HGW from all sources was expected to reach 22,000 (Sailer 2008) to 29,000 m^3 (BfS 2008) by 2040 under the year 2000 phase-out law. The BfS estimate corresponds to 17,200 tHM by 2040, 46% higher than today (Table 3). In 2010 the implementation of the nuclear phase-out was postponed until 2036. Assuming licences would not be limited to 32 years but extended to 60 years, similar to what has been common practice in the USA, this would imply an additional 21,400 m^3 of NHGW by 2040 (Table 3), or an increase of roughly 8% (BfS 2008). In this scenario, cumulative amounts of HGW by 2040 would increase by 11,700 tHM or 68% (BfS 2008). The difference in relative change is due to the large share of NHGW in decommissioning.

2.2.2 Geological Formations for Radioactive Waste Disposal

Deep geological disposal of RW has been the only legal option for final disposal of both NHGW and HGW in Germany since the amendment of the Atomic Energy Act in 1975. Disposal is considered a national responsibility and therefore disposal abroad is illegal. An extensive knowledge base has been built in Germany on suitable geological formations, especially salt domes, which have been thoroughly surveyed, researched and field tested since the 1960s. The focus has been on salt formations, but crystalline rock formations and, more recently, argillaceous rock formations have been explored in detail (BGR 2007). Results of this work have been summarized in a series of reports by the BGR, commissioned by the German Government, in particular on HGW disposal in salt formations (so-called *Salzstudie*) (Kockel and Krull 1995), HGW disposal in crystalline formations (so-called *Kristallinstudie*) (Bräuer et al. 1994), and NHGW disposal in claystone (Hoth et al. 2005 and 2007). In addition to these technical reports, the BMU has commissioned a comprehensive review study of RW disposal that also includes socio-political issues (Brasser et al. 2008).

A long series of lists of minimum requirements and criteria for repository sites have been suggested and used over the past 40 years. While the more recent lists also include socio-political elements that were not part of the earlier lists, there are hardly any differences in terms of the geological criteria considered (Appel 2008). The geological criteria recommended by the German Government's task force AkEnd (2002) are summarized in Table 4. The criteria contained in the first evaluation step imply that salt formations and argillaceous rock formations are the only suitable formations satisfying the criterion of very low permeability, as crystalline rock formations may be permeable because of fractures.

Table 3 Projections for cumulative radioactive waste in Germany 2000–2040 (in m^3)

			2040	2040	2040	2040
Year (end)	2000	2007	BfS estimate (32-year licences, no reprocessing)	WRB estimate (32-year licences, higher unit waste assumptions)	EWN estimate (assuming waste minimization strategy)	BfS estimate (licence extensions to 60 years)
Negligible heat generating waste	76,000	118,124	277,000	297,000	192,000	298,400
Heat generating waste	8,400	14,900	22,000[a]–29,000 (17,200 tHM)	24,000	n.a.	48,000 (28,900 tHM)

Sources: BfS 2008; Witherspoon and Bodvarsson 2006; and authors' estimates
BfS Bundesamt für Strahlenschutz, *EWN* Energiewerke Nord, *WRB* World Reference Base
[a] Sailer 2008

Table 4 Main requirements and criteria for repository sites suggested by AkEnd (2002)

Criterion	First evaluation step	Second evaluation step
Seismic activity	Must not exceed Earthquake Zone 1 (DIN 4149)	–
Volcanic activity	No quaternary or expected future volcanism	–
Thickness of the isolating rock zone	>100 m; rock types with field hydraulic conductivity of <10^{-10} m/s	>500 m for rock salt deposits in salt domes (Kockel and Krull 1995)
Depth of the top of the isolating rock zone	>300 m	Salt roof above repository zone > 300 m; cover rock over salt dome > 200 m and impermeable to water
Underground depth of the repository	<1,500 m	<1,000 m for argillaceous rock formations
Minimum area of the isolating rock zone	>10 km² in claystone	>3 km² (AkEnd 2002) and >9 km² (Kockel and Krull 1995) for salt dome
Research findings	No findings that raise doubt that field hydraulic conductivity, thickness and extent of the isolating rock zone can be fulfilled for 1 million years	–
Other	–	Rock salt not affected by any other mining or drilling

Note: Second evaluation step supplemented with recommendations by Kockel and Krull (1995), as reported in BGR (2007)

There is an extensive body of knowledge on rock salt formations in Germany, which have been thoroughly researched for the past 60 years; several hundred years of salt mining experience in Germany can also be drawn upon. For example, the BGR draws on data sources from more than 25,000 boreholes across Germany at depths of more than 300 m (Bräuer 2008). Disposal of RW is planned in drifts and deep boreholes at a maximum depth of roughly 900 m, using crushed salt as backfill. Rock salt has a number of favourable properties for RW disposal. In particular, it is almost impermeable to liquids and gas, has a very high heat conductivity and heat resistance, and shows visco-plastic deformation behaviour. The design temperature is 200°C, and no drift reinforcement structures are necessary, which makes rock salt suitable for disposal of both NHGW and HGW.

Rock salt formations in northern Germany (and to a lesser extent southern Germany) occur in the form of salt domes and stratiform rock salt deposits. BGR's *Salzstudie* (Kockel and Krull 1995) assessed more than 200 salt formations in Germany for their suitability as repositories for RW. BGR (2007) considers the Hauptsalz of the Staßfurt Formation in North Germany to be the only formation which 'is known to have uniformly good host rock properties throughout, and to form very thick deposits'. The stratiform salt deposits in the Zechstein Basin are considered as a backup option. While the Rotliegend rock salt in north-west Germany is very thick in some places, it occurs 'in salt domes with very complicated internal structures' (BGR 2007). The Zechstein salts of the Aller to Mölln Formation, as well as the Upper Bunter, Muschelkalk and Tertiary rock salts are too thin. The Keuper salts, the Upper Jurassic rock salts and the stratiform salt deposits of the Werra district are considered unsuitable. In addition to the Gorleben salt dome, in 1995 the BGR reassessed the salt domes in northern Germany and identified a range of salt formations worth investigating at Wahn, Zwischenahn, Gülze-Sumte and Waddekath (Bräuer 2008).

Comparatively less knowledge exists on argillaceous rock formations and their suitability as repositories. Disposal of RW is planned in drifts or shallow boreholes at depths of roughly 500 m, using bentonite as backfill. Among the advantages of argillaceous rock formations are their low permeability and low dissolution behaviour. However, their low heat conductivity and low heat resistance is considered a problem and limits design temperatures to less than 100°C. There is also a need for man-made drift reinforcement structures, which would be a particular problem at great depths (BGR 2007).

While argillaceous rock formations at desired depths and thickness are found in the Tertiary, Cretaceous and Jurassic in both northern and southern Germany (BGR 2007), a wide range of such formations have been considered unsuitable by BGR (2007), including the argillaceous rock formations in the Upper Rhine Graben (earthquake zone), Tertiary clays in northern Germany (low level of consolidation), Tertiary clays and claystones of the Alpine Foreland Basin (minor consolidation only), Opalinus Clay formation (proximity to exploited karst aquifer, partly in an earthquake zone) and areas with extremely steep bedding near salt structures. The investigation focus is thus on thick argillaceous rock formations in the Northern Cretaceous sequence and the North and South German Jurassic sequences (BGR 2007; Hoth et al. 2005, 2007).

Crystalline rock formations are geologically well mapped in Germany, and it is possible to draw on significant mining experience. Disposal of the nuclear waste is planned in drifts or boreholes at a depth of 500–1,200 m, using bentonite as backfill (BGR 2007). The advantages of crystalline rock are its high strength and cavity stability, its low heat sensitivity and very low dissolution properties. However, its brittle deformation behaviour and anisotropic in situ stress behaviour is considered problematic. Most importantly, crystalline rocks when fractured show unsuitably high permeability. Man-made drift reinforcement would be necessary in fractured zones, limiting design temperatures to less than 100°C (because of the bentonite backfill). In 1995 the BGR identified ten crystalline formations for further investigation, including formations at Saldenburg, Nördlicher Oberpfälzer Wald, Fichtelgebirge, Graugneis, Granulitgebirge, Pretzsch, Prettin, Pulsnitz, Radeberg-Löbau and Zawidow (Bräuer 2008). In 2007 the BGR concluded that it is 'unlikely that Germany has zones of homogenous and unfractured crystalline rocks large enough for the construction of a nuclear repository mine' (BGR 2007).

2.2.3 Locations and Capacity Estimates

Since the 1960s West Germany has stored a total of 47,000 m^3 of NHGW at a 'test disposal facility' in the Asse salt mine (Sailer 2008). Former East Germany operated the Morsleben salt mine where 36,753 m^3 of NHGW were disposed of between 1971 and 1998. After a quarter of a century of legal battles, a final court decision (*unanfechtbarer Planfestellungsbeschluss*) awarded an operating licence for the Konrad iron ore mine, and it is expected to open for NHGW disposal in 2013 (Sailer 2008). The Gorleben salt dome was selected as a disposal site for HGW some 30 years ago; however, its development has been constrained by strongly opposing political views.

The *Konrad Mine* is a former iron ore mine near the town of Salzgitter in the state of Lower Saxony in northern Germany. The target layer for disposal in the Konrad mine is the iron ore layer at depths of 800–1,300 m. The ore deposit is quite unique in that it is very dry and fairly deep and was deposited in the Upper Jurassic 150 million years ago (Biurrun and Hartje 2003). The iron ore is overlain by highly impermeable Cretaceous claystone and marlstone (Sailer 2008). From 1960 to 1976, iron ore was mined at Konrad at great depths of 900–1,300 m. The mine extends over a 1.4 by 3.0 km area. Only 6.7 Mt of iron was mined, accounting for 0.5% of the resources. Extensive geoscientific exploration and investigations assessed the site's suitability to host a final repository for RW, concluding that the mine was very suitable for the disposal of both HGW and NHGW (Biurrun and Hartje 2003). From 1976 to 1982 the German Government commissioned the Gesellschaft für Strahlen- und Umweltforschung mbH (GSF) to conduct a geological, seismic and geotechnical study which showed that the site was ideal for the final disposal of NHGW. From 1983 to 1990, the site was further investigated, and a safety report, the Konrad Plan, was issued in 1991. While the Konrad mine could accommodate an estimated 650,000 m^3 of waste, the approved licence is only for 303,000 m^3, which would be more than enough for all NHGW from German reactors, including decommissioning and all other sources.

The *Gorleben salt dome* is one of many salt domes in the North German Basin. The suitability of Gorleben as a final repository for disposal of all types of RW has been under investigation since 1979. An extensive number of seismological surveys and geophysical measurements were carried out until the government moratorium on exploration in 2000. The salt dome consists of massive formations of Zechstein salt. Large homogeneous salt areas were found in the Staßfurt sequence of the Zechstein, which are particularly suitable for RW disposal (Brasser et al. 2008). It should also be noted that an almost complete sequence of principally clayey-silty marine sediments from the Upper Paleocene onwards is preserved. The salt dome covers an area of about 14 by 4 km. The top of the salt dome is 250 m below the surface and the salt base at depths of 3,200–3,400 m. In 1986 two shafts (Gorleben 1 at 933 m and Gorleben 2 at 840 m) were constructed with the main gallery at a depth of 840 m. In total, about 7 km of drifts and galleries with a volume of 234,000 m^3 have been excavated, and geological and geotechnical boreholes with a total length of 16 km have been drilled (Brasser et al. 2008). In order for Gorleben to become operational, political agreement would need to be reached and a site plan approval procedure completed.

The former *salt mine Asse*, close to the town of Remlingen in the district of Wolfenbüttel, was explored and used as a repository for R&D from 1965 to 1995 (Brasser et al. 2008). From 1967 to 1978, LLW and ILW was stored at Asse in 13 chambers at depths of 511, 725 and 750 m. In contrast to Gorleben, extensive salt mining took place at Asse from 1909 to 1964, which has led to mechanical instabilities that make the site unsuitable for long-term disposal.

The Former German Democratic Republic (East Germany) licensed the *Morsleben Repository for Radioactive Waste* (Endlager für radioaktive Abfälle Morsleben (ERAM)) in 1981. It was operated for NHGW until 1998. There was storage of LLW and ILW in the twin salt mines of Bartensleben and Marie in the state of Sachsen-Anhalt near the villages of Morsleben and Beendorf. The twin mine is 5.6 km long and 1.7 km wide, whereas the overall salt deposit covers an area of 50 by 2 km. Mining took place for 70 years until 1969 (Brasser et al. 2008). Two shafts connect to a system of drifts, cavities and blind shafts at depths of 320–630 m below the surface, amounting to a volume of roughly 6 million m^3. (Another 2 million m^3 were backfilled with crushed salt.) The drifts for the final disposal are located in the mine's periphery. The centre appears to be stressed (Kreienmeyer et al. 2004). The ERAM was constructed in Zechstein salt strata, with Staßfurt, Leine and Aller Formations being exposed in the repository mine (Behlau and Mingerzahn 2001). ERAM is located in the Allertalzone structure, which is a fault structure separating the Lappwald block and the Weferlinger Triassic block. Permian evaporate strata intruded into the fault zone and accumulated in a plug, forming the present salt structure. The Zechstein salt deposit has a thickness of 380–500 m and the salt leaching surface is about 140 m (maximum 175 m) below mean sea level. The salt body includes a high amount of anhydrite layers of the Leine sequence which stabilize the salt structure and lead to low convergence of mine excavations (Kreienmeyer et al. 2004). It also includes potash seams, mainly carnallitite and kiseritic hard salt. The caprock has a very low hydraulic conductivity and isolates the salt structure from the aquifers in the overlying upper Cretaceous formations. Above the aquifers there are unconsolidated or semi-consolidated glacial sediments and the surface cover consists of Quaternary sediments (Kreienmeyer et al. 2004).

We have not been able to find any published overall national estimates of geological RW disposal capacity for Germany. Quoted capacities are 650,000 m^3 for the Konrad mine, several million cubic metre for the Morsleben mines. Assuming conservatively that at least 10 of the 140 salt domes previously investigated in northern Germany would prove suitable for geological disposal of nuclear waste, national capacity will be at least 10 million m^3. This exceeds the country's cumulative expected nuclear waste volume from all sources for 1970–2040 by one to two orders of magnitude; this implies that the geological storage capacity is large enough for hundreds of years of large-scale nuclear power generation, assuming no waste minimization strategy.

2.2.4 Implementation Issues

Compared to fossil-fired power plants, the use of nuclear power in Germany means that 100–150 Mt CO_2 emissions are avoided every year, which is similar to the annual national emissions from vehicular traffic (BMWi 2009). This has been a convincing argument against the nuclear phase-out, as most Germans are increasingly concerned about anthropogenic climate change. In fact, a public survey carried out in June 2007 showed that 63% of Germans did not believe in the feasibility of the phase-out and that there was a stable majority of Germans in favour of nuclear power in the long run (Koecher 2007). In other words, a great deal of uncertainty remains about the future of nuclear power in Germany.

In Germany, geological disposal of RW is governed by the Atomic Energy Act of 1959 and its subsequent revisions, as well as the mining law (Bergbaugesetz). Disposal of RW is the sovereign task of the Federal Government. The BMU is responsible for nuclear safety and radiation protection. Operational tasks are managed by the BfS which is supervised by the ministry. The BMWi supervises the BGR, which advises the German Government in all geological and geotechnical matters.

The issues of nuclear power in general and RW disposal in particular have been highly politicized both in the national public debate as well as at government level. While a nuclear phase-out decision was taken in 2000 by the then ruling government, somewhat contradictory views are expressed within the main political parties and also within the current federal government that postponed the phase-out by revising the law in 2010. In fact, while the BMU has taken a rather anti-nuclear stance, the BMWi has highlighted the importance of the continued use of nuclear power and the need to make geological repositories for RW disposal operational. The anti-nuclear side succeeded in imposing an investigation moratorium on the Gorleben site and in setting up the government task force, AKEnd, in 1999, which suggested that a new selection process for repository sites be started with a 'white map of Germany' (Sailer 2008). Another point of disagreement in the Government is the issue of whether to pursue the development of a single national geological repository or several. A recent study carried out by the BfS and the Gesellschaft für Reaktor- und Anlagensicherheit (GRS) mbH showed that the single-repository concept would cause additional costs of several billion euros which would be more than the total cost of the construction, operation and decommissioning of the Konrad repository. While the additional costs for the single-repository concept would have to be fully financed from public funds, two thirds of the cost of constructing and operating the Konrad repository had to be borne by the industry (Pfeiffer 2007).

Public opinion was also polarized on the issues. While in the late 1980s and early 1990s the majority of the public had concerns about nuclear power use, this now seems to have changed. In fact, in 2007, 63% of Germans believed that the country would not abstain from the use of nuclear power in the long run, compared to only 18% who believed that the year 2000 phase-out agreement would be completed (Koecher 2007). Eighty per cent of German businesses are in favour of extending the operating lifetime of the country's nuclear power plants beyond the phase-out dates of the year 2000 law, according to a survey of the German Association of Chambers of Industry and Commerce (WNN 2008).

Because of such polarized views in Germany, the history of developing geological repositories for RW has been characterized by decades of legal challenges and socio-political conflicts. In 1982 the predecessor of BfS applied for a construction and operating licence for a NHGW final disposal site at the Konrad mine. Following the Konrad plan in 1991, extensive public consultations were held in which 289,387 persons formally raised issues that were summarized into more than 1,000 themes. In view of the political and legal opposition, the German state of Niedersachsen approved the licence only in 2002, and it took until 2007 for the highest administrative court to rule in favour of the site. All legal means have been exhausted (*unanfechtbarer Planfestellungsbeschluss*), but political opposition continues. The technology for storage and backfilling of the cavities is available and was tested by DBE. Planning for the facility is under way and it is expected to open in 2013 (Sailer 2008).

In 1976 the state government of Niedersachsen preselected 4 out of 140 salt domes that had been investigated as potential sites for NHGW/HGW repositories (Gorleben, Lichtenhorst, Mariaglueck and Wahn). Using geological and socio-political criteria, and also in view of the fact that it is one of the largest unmined salt domes in Germany, the state government selected Gorleben. In 1977, the German Federal Government confirmed the choice (Brasser et al. 2008). As part of the nuclear phase-out policy decision in 2000, the Government imposed a moratorium (of 3–10 years) on further exploration and preparation of the Gorleben site. To start implementation, a site plan approval procedure needs to be completed and all legal challenges considered. This process took 25 years in the case of the Konrad site.

The former German Democratic Republic (East Germany) carried out safety and techno-economic assessments and explored the disposal of LLW and ILW at Morsleben from the 1960s onward. The site was selected as a geological repository in 1972, and between 1981 and 1998 some 36,800 m^3 of RW were stored there. A few years after German reunification, the German Government decided to stop waste disposal at the site in 1998 and to prohibit it in 2002. Since 2005 the site has been under licensing for closure. In the next 10–15 years backfilling and sealing is planned. Nevertheless, some geologists continue to believe that the potash and rock salt cavities would have been promising properties for a long-term repository (Preuss et al. 2002).

There is a wide range of cost estimates for geological disposal of RW in Germany, many of which appear politically motivated. The most objective estimates are available for the Konrad repository. These data are the most reliable as they relate to the real financial liabilities of the private and public sectors. Aggregate costs for exploratory and planning activities for the Konrad repository amounted to €945 million by 2007. Costs for converting the mine will amount to approximately €900 million. Annual costs for keeping the Konrad mine open are €18.5 million. Overall life cycle cost estimates are around €10,000–25,000/m^3 (BfS 2009). The low estimate is based on low waste volumes (200,000 m^3) and a long life cycle until 2080, and the high estimate assumes higher waste volume (290,000 m^3) and a short life cycle until 2040.

2.3 Comparison of Geological Disposal of CO_2 and Radioactive Waste in Germany

This section compares the geological disposal of CO_2 and RW in Germany. It identifies the major differences and similarities in terms of geological environment, rock type and characteristics, safety potential, mode and purpose of disposal, volume (disposal capacity), disposal depth, containment mode, site selection and public acceptance, and implementation issues. Table 5 summarizes the key results.

Disposal of CO_2 and RW is pursued in rather different geological environments. All promising CO_2 disposal options are based on the permeability of high-porosity geological target formations below low-permeability caprock cover. Examples are deep saline aquifers, deep-lying depleted oil- and gasfields, and deep coal seams. Exceptions are closed coal mines and salt caverns that had once been investigated, but are not longer considered suitable. In contrast, RW disposal is pursued in low-permeability rocks with geological stability and low groundwater fluxes. These include rock salt formations in the form of salt domes and stratiform rock salt deposits (e.g. the Gorleben, Morsleben and Asse repositories), argillaceous rock formations, and the unique case of the deep and very dry Konrad iron ore mine. Crystalline rock formations are considered unsuitable because of fractures.

The most promising target rock types for disposal differ greatly. It is interesting to note, however, that the preferred caprocks for potential CO_2 storage reservoirs include Zechstein salt and Jurassic clay formations, both of which are also preferred rock types for RW repositories. For example, CO_2 disposal in the gasfield at Altmark occurs in red sandstone and siltstone with shale layers, overlain by several hundred metres of Zechstein salt bedrock. CO_2 disposal in the sandstone aquifer at Ketzin occurs in a Stuttgart Formation of Triassic age with a Triassic Weser Formation as top seal. CO_2 disposal in the saline aquifer at Schweinrich occurs in layers of sandstones (Lower Jurassic and Uppermost Triassic) overlain with thick Jurassic clay formations. In contrast, RW disposal is preferred in rock salt formations, as they are almost impermeable to liquids and gas, show very high heat conductivity and heat resistance, visco-plastic deformation behaviour, and achieve design temperatures of 200°C with no drift reinforcement structures necessary. The preferred rock type is the Hauptsalz of the Staßfurt Formation (e.g. the Gorleben repository). Stratiform salt deposits at the Zechstein Basin are considered a backup option. Disposal in argillaceous rocks is also explored because of their low permeability and low dissolution behaviour, despite the low heat conductivity and heat resistance with lower design temperatures of 100°C. In this context, investigation focuses on thick argillaceous rock formations in the Northern Cretaceous sequence and the North and South German Jurassic sequences.

CO_2 and RW disposal both have a high safety potential. However, whereas the technology for RW disposal is mature and safe, this is only the case for CO_2 disposal in depleted oil-/gasfields. General risks of CO_2 disposal are considered manageable for depleted oil-/gasfields, whereas important challenges and concerns (e.g. usage conflicts) remain in the case of saline aquifers and coal seams, even though long-term stability is considered good in these two cases.

The technology for RW disposal in salt formations has been developed for several decades and is considered safe by experts. It also takes into account extreme risks such as earthquakes, tectonic movements and the potential impact of a new ice age. Furthermore, safety regulations limit radioactive exposure close to the repository to

Table 5 Comparison of geological disposal of CO_2 and radioactive waste in Germany

Criteria	Carbon dioxide	Radioactive waste
Geological environment	Primarily: deep, permeable, high-porosity geological formations with low-permeability caprock cover	Low-permeability rock with geological stability and low groundwater fluxes
Rock type and characteristics	*Sandstone and saline aquifers*: Stuttgart Formation of Triassic age with a Triassic Weser Formation as top seal; or Lower Jurassic and Uppermost Triassic sandstone layers with Jurassic clay formations on top	*Rock salt formations*: Hauptsalz of the Staßfurt Formation, or stratiform salt deposits at the Zechstein Basin
	Gasfield: red sandstone and siltstone overlayed by Zechstein salt bedrock	*Thick argillaceous rock formations* in the Northern Cretaceous sequence and the North and South German Jurassic sequences
Mode and purpose of disposal	*Mode*: Injection of liquid supercritical CO_2 through well and boreholes, or controlled heating of liquid CO_2 at high pressures	*Mode*: Emplacement in gallery via shafts and boreholes
	Purpose: EGR, EOR, ECBM or just disposal in aquifer	*Purpose*: Safe and secure, final disposal
Volume (disposal capacity)	*National technical disposal capacity:* 19–48 Gt CO_2 or 30–60 years of CO_2 emissions from all large stationary sources in Germany	*National technical disposal capacity*: >10 million m^3 or hundreds of years of expanded nuclear power generation, not taking into account waste minimization
	By type: Saline aquifers (12–28 Gt CO_2), depleted gasfields (2.56 Gt), oilfields (0.110 Gt), coal seams (3.7–16.7 Gt)	*Konrad site alone*: 650,000 m^3, but licensed for 303,000 m^3 (i.e. more than the country's cumulative radioactive waste from all sources 1970–2040)
Depth	650 m–3,500 m	320–1,300 m
Containment mode	Natural barriers with very low permeability	*Natural barriers* of highly impermeable formations
		Man-made barriers: (a) Backfill/sealing with crushed salt or betonite; (b) drift reinforcement structures in clay and crystalline formations

(continued)

Table 5 (continued)

Criteria	Carbon dioxide	Radioactive waste
Site selection and public acceptance	Researchers and private sector select sites	Government-organized selection process among over 200 salt formations. Forty years of official site selection criteria. Licensing of the Konrad site took 25 years
	No public debate due to limited knowledge. Experts and industry representatives are optimistic, environmental NGOs increasingly uneasy or opposed to CCD	Radioactive waste issue highly politicized. Polarized views on Government's nuclear phase-out decision. Majority of Germans do not believe in the phase-out
Implementation issues	German CCS Act passed in 2009, but strongly criticized by environmental NGOs. *Standards* and criteria for CO_2 disposal sites	Sovereign task of the government (German Atomic Energy Act of 1959 and revisions, Mining Law). Konrad site (operational by 2013) the only geological repository with a valid licence
	Estimated costs: 2.56 Gt CO_2 at €6.5/t in depleted gas fields, 12–28 Gt/CO_2 at €8/t in saline aquifers, 3.7–16.7 Gt/CO_2 at €13/t in deep coal seams	*Estimated costs*: €10,000–25,000 per m^3 of RW (life cycle basis, Konrad mine)

CCD carbon capture and disposal, *ECBM* enhanced coalbed methane (recovery), *EGR* enhanced gas recovery, *EOR* enhanced oil recovery, *NGOs* non-governmental organizations

levels within the natural range between different regions (less than 0.8 mSv/year at the Konrad site). CO_2 is injected whereas RW is emplaced. In contrast to RW disposal, some CO_2 disposal options serve additional purposes besides final disposal. More specifically, CO_2 is injected in liquid supercritical state through wells and boreholes or, alternatively, liquid CO_2 at high pressures is heated in a controlled way. In the case of storage in an aquifer, the only purpose is final disposal, whereas CO_2 injection can also be used for EGR, EOR and ECBM. In contrast, the only purpose of RW emplacement in galleries (via shafts and boreholes) is its safe and secure final disposal.

In absolute terms, the technical potential for CO_2 disposal is large and about two orders of magnitude larger than the technical potential for geological disposal of RW in Germany. Yet, relative to the waste volumes to be disposed of, the potential for RW disposal is at least one order of magnitude larger than for CO_2. The national technical disposal potential is estimated at 19–48 Gt CO_2, which is equivalent to 30–60 years of CO_2 emissions from all large stationary sources in Germany (although the BGR estimate is more conservative, namely 20 ± 8 Gt CO_2). More specifically, capacity estimates are in the range of 12–28 Gt CO_2 in saline aquifers, 2.56 Gt in depleted gasfields, 0.11 Gt in oilfields and 3.7–16.7 Gt in coal seams.

The total national technical geological RW disposal capacity is more than 10 million m^3 (about 200 Mt), which is large enough for hundreds of years of expanded nuclear power generation, not taking into account any waste minimization strategy. The technical storage potential is about 650,000 m^3 for the Konrad site alone and several million cubic metre for the Morsleben site. The Konrad site is licensed for only 303,000 m^3, which is still more than the country's cumulative expected RW from all sources from 1970 to 2040.

While CO_2 disposal is explored mainly at depths of more than 1,000 m, RW disposal is pursued primarily at depths of less than 1,000 m. Examples of CO_2 disposal depths include 650 m (Ketzin aquifer), 1,500–1,600 m (Schweinrich aquifer) and 3.5 km (Altmark gasfield). Examples of RW disposal depths include 800–1,300 m (Konrad iron ore mine), 840–933 m (Gorleben salt dome) and 320–630 m (Morsleben salt mine).

CO_2 disposal is based on natural barriers with very low permeability while RW disposal includes both natural and man-made barriers. Examples of natural barriers with very low permeability include 100 m thick Zechstein salt bedrock in the case of the Altmark gasfield and thick Jurassic clay formations in the case of the Schweinrich saline aquifer. Examples of natural barriers in the case of RW disposal include several hundred metres of highly impermeable Cretaceous claystone and marlstone in the case of the Konrad site, and several hundred metres of unmined salt dome in the case of the Gorleben site. Engineered barriers around the waste packages include backfill and sealing for which crushed salt is used in salt formations and bentonite in clay and crystalline formations. Man-made drift reinforcement structures are needed for potential repositories in clay and crystalline formations.

Whereas the site selection for CO_2 disposal is carried out by researchers and the private sector with hardly any government involvement, site selection is a government-driven process in the case of RW disposal. The German public does not yet debate the pros and cons of CCD because of limited knowledge. While experts and industry representatives are generally optimistic about CCD, environmental organizations have expressed their uneasiness or outright opposition. In the case of RW disposal, site selection criteria have been officially adopted and have barely changed in the past 40 years, except for the increasing prominence of socio-political aspects. Despite an exhaustive selection process covering more than 200 salt formations organized by the Government, a government task force in 2002 suggested that the site selection process be restarted from scratch. The licensing of the Konrad site took 25 years and included public consultations in which 289,387 persons formally raised issues on over 1,000 themes. The RW disposal issue has been highly politicized and polarized both in government and among the public. The majority of Germans do not believe in the feasibility of the nuclear phase-out in the long run, and the overwhelming majority of German businesses favour an extension of the operating lifetimes of Germany's NPPs.

While the legal basis for RW disposal has been in place for 50 years, that for CO_2 disposal has emerged only recently. Estimated disposal costs are about two orders of magnitude greater per tonne of RW compared to CO_2. The German CCD act was passed in early 2009. It has been criticized by non-governmental organizations. The BGR is also developing standards and criteria for CO_2 disposal sites. For example, DIN standards exist, such as DIN EN 1918-1 on gas storage in aquifers and DIN EN 1918-2 on gas storage in oil-/gasfields. Geological disposal of RW has been governed by the German Atomic Energy Act of 1959, its revisions, and the Mining Law. The RW disposal is a sovereign task of the government. To date, only the Konrad site has a valid licence that is no longer subject to legal challenges. The site will be operational by 2013.

While large uncertainties remain in terms of costs and capacities, an estimated 2.56 Gt CO_2 could be stored for about 6.5 €/t in depleted gasfields, 12–28 Gt CO2 for 8 €/t in saline aquifers, and 3.7–16.7 Gt CO_2 for 13 €/t in deep coal seams. In contrast, the costs of storing the cumulative RW of Germany from 1970 to 2040 in the Konrad mine are about €10,000–€25,000/m^3 on a life cycle basis.

In conclusion, while CO_2 disposal differs greatly form RW disposal in Germany in technical terms, important lessons can be learned for CO_2 disposal from the RW experience. In particular, similar public acceptance issues are likely to surface in the future requiring a similarly large-scale need for public consultation and very long time frames. A big difference is the much larger amounts of CO_2 needing to be disposed of compared to RW, which has important implications for their management. It may very well be that experts greatly overestimate the socio-political potential for CO_2 disposal in Germany.

3 France

3.1 CO_2 Sources and Geological Disposal in France: Status and Issues

3.1.1 Fossil-Based Electricity and CO_2 Emissions

In France an estimated 390 Mt CO_2 was emitted in 2005 from fossil fuel combustion, of which electricity and heat production accounted for 14.6% (56.6 Mt CO_2) (IEA 2008a, b). In 2006, 78% of electricity was produced by nuclear power in France (IEA 2008c), which, together with hydropower, supplies most of the baseload power. Fossil fuel-based plants, accounting for 9% of gross electricity production, are mainly operated to meet peak demands, which generally occur under extreme weather conditions. France's dependence on nuclear power is partly due to its lack of domestic fossil energy resources. Fifty-two per cent of total primary energy supply is accounted for by fossil fuels, of which only 1.5% is produced domestically.

Consequently, France has relatively low CO_2 emissions per unit of electricity generated (91 g CO_2/kWh in comparison to the world average of 502 g CO_2/kWh and the OECD average of 442 g CO_2/kWh in 2005). Total CO_2 emissions per capita are much lower than the OECD average, and the CO_2 reduction commitment of France under the Kyoto Protocol is modest. However, the Government has highlighted the need for further CO_2 emission reductions. Thus, the technological challenges to further reduce GHG emissions are a high-priority R&D issue in France (Brosse 2005).

France's principal CO_2 emission sources are concentrated in five main areas, as presented in Fig. 4 (Bonijoly et al. 2003): Nord-Lorraine (Lorraine region), Basse-Seine (Haute-Normandie region), Golfe de Fos (Provence-Alpes-Côte d'Azur region), Dunkerque (Nord-Pas de Calais region) and the Loire estuary (Pays de la Loire region). The regions of the Paris Basin alone account for 61% of CO_2 emissions of the industrial and energy sectors in France. The search for CO_2 disposal sites has been limited primarily to the immediate proximity (not more than tens of kilometre) of the major emission sources in view of concerns about accidents and the high costs related to CO_2 transportation by pipeline (Bonijoly et al. 2003).

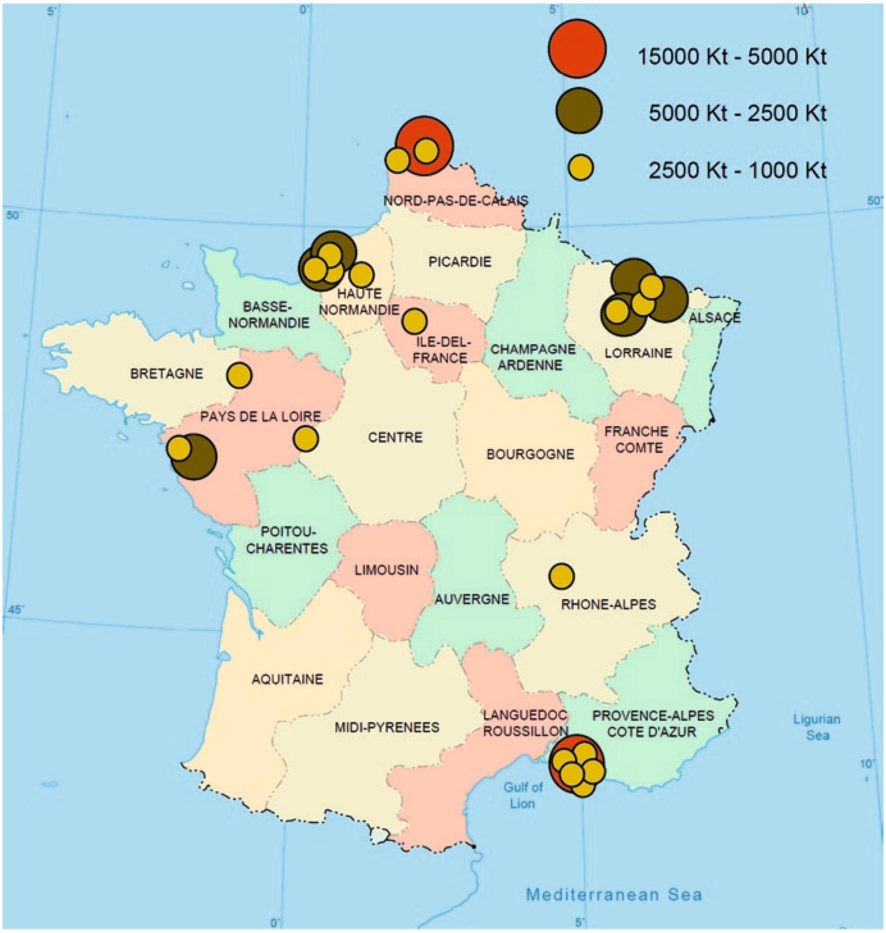

Fig. 4 Major sources of CO_2 emissions (Data taken from the Registre français des emissions polluantes 2009) (see *Colour Plates*)

3.1.2 Geological Formations for CO_2 Disposal

In France, four types of geological formations are under consideration for the disposal of CO_2: aquifer reservoirs, hydrocarbon deposits, coalbeds and basic and ultrabasic formations (such as basalts, periodotites or serpentinites), with decreasing expected disposal potential in this order. Aquifer reservoirs are found in sedimentary basins. There are three major basins: the Paris Basin, the Aquitaine Basin and the South-East Basin (see Fig. 5). Many of the assessments to date have been conducted for the Paris Basin, in view of its proximity to the largest sources of emissions. The locations and capacities of hydrocarbon deposits are well known to major oil and gas companies. Details are not necessarily disclosed to the public. Coalbeds have been evaluated in terms of their potential CO_2 storage capacity in the area of Marseille. The principal form of disposal in basic and ultrabasic formations is mineral sequestration. In Europe, 11.7% of French territory has these formations, especially the Massif Central. New Caledonia, Reunion and Corsica also have such formations (Bonijoly et al. 2009; BRGM 2008).

Within the framework of the European GESTCO project, aquifers in the Paris Basin were identified and assessed (Bonijoly et al. 2003). The most favourable geological conditions were defined as: (1) permeable rock more than 1,000 m deep; (2) an impermeable cover to ensure storage security by preventing gas return to the biosphere; and (3) a suitable structure (i.e. trap) to limit lateral transfers of CO_2.

Fig. 5 Location of the Paris Basin (*upper marked area*), the Aquitaine Basin (*lower left marked area*) and the South-East Basin (*lower right marked area*) (Adapted from Bonijoly et al. 2006)

Injected CO_2 is expected to rise buoyantly to the top of the reservoir structure and accumulate beneath the caprock, a porous material of low permeability saturated with brine. Efficient caprocks are usually composed of salt or clay formations. Such low-permeability rocks are well known in France, because they are considered to be good candidates for RW disposal.

Environmental issues also play an important role in the search for CO_2 disposal sites. Under the PICOREF (Piégeage du CO_2 dans les réservoirs géologiques en France (CO_2 trapping in reservoirs in France)) project, environmental reviews of potential CO_2 disposal sites in the Paris Basin were carried out (Blanchard 2006). The project included R&D on CO_2 disposal with a focus on site identification and evaluation in France (Brosse 2005). The main environmental issues considered were the protection of water resources and biodiversity. The project created maps to support decision making on the question of siting.

3.1.3 Locations and Capacity Estimates

One third of the land area of France is underlain by sedimentary basins that could contain aquifers suitable for CO_2 disposal. The EU project JOULEII provided estimates of the national CO_2 disposal capacities. In particular, the capacity of the trapped fraction of all aquifers in France is estimated at 1.5 Gt CO_2, with 0.3 Gt for the Paris Basin and the rest for the Aquitaine Basin (Barbier 1996).

The feasibility of CO_2 disposal and estimates of capacities in the Paris Basin were evaluated under the GESTCO project (Bonijoly et al. 2003). The Paris Basin occupies about half of northern France and is composed primarily of Mesozoic rock. The main reservoir beds are shown in Fig. 6. Among these reservoirs, only Triassic sandstone-conglomerate layers of the Bundsandstein (upper part of Triassic sandstone), the Keuper (lower part of Triassic sandstone), and the Dogger oolitic limestone were identified as having the desirable geological properties for CO_2 disposal.

The Bundsandstein reservoirs are found mainly in the Lorraine region and the lower part of Champagne-Ardennes region, covering an area of about 21,000 km^2. The depth of the top of the Bundsandstein sandstone increases westwards from the edge of the exposure, reaching 1,800 m. The average thickness is 200 m, with some areas exceeding 400 m. The Keuper sandstone is found mainly in the Île-de-France region and the western part of the Centre region, also stretching into neighbouring regions and covering an area of about 27,500 km^2. The average thickness is 25 m with some areas exceeding 300–400 m, and the maximum depth of the top of the layer is about 2,800 m. These two reservoir beds in Triassic formations are among the largest aquifer reservoirs in the Paris Basin.

The Dogger reservoir covers a large area including the regions of Haute Normandie, Picardie, Île-de-France, a large part of Champagne-Ardennes and the northern part of Bourgogne, covering a total area of 15,000 km^2. In the central and the western sector, the thickness of the reservoir is more than 150 and 175 m, respectively. The depth of the top of the layer is in the range of 1,100–1,800 m.

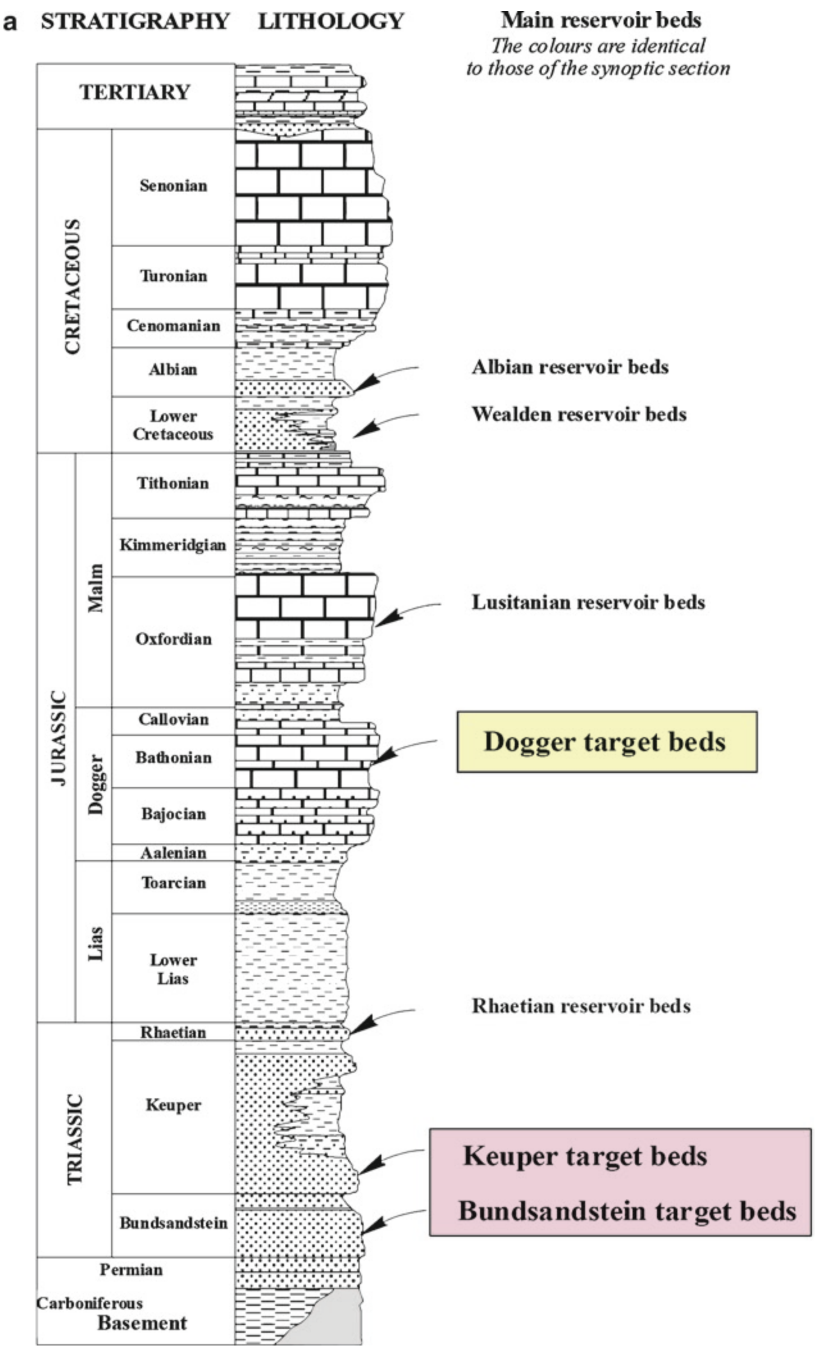

Fig. 6 Geological formations and main CO_2 reservoirs in the Paris Basin (Source: Bonijoly et al. 2003) (*see* Colour Plates) Panel **a**. Synoptic log of sedimentary formations in the Paris Basin

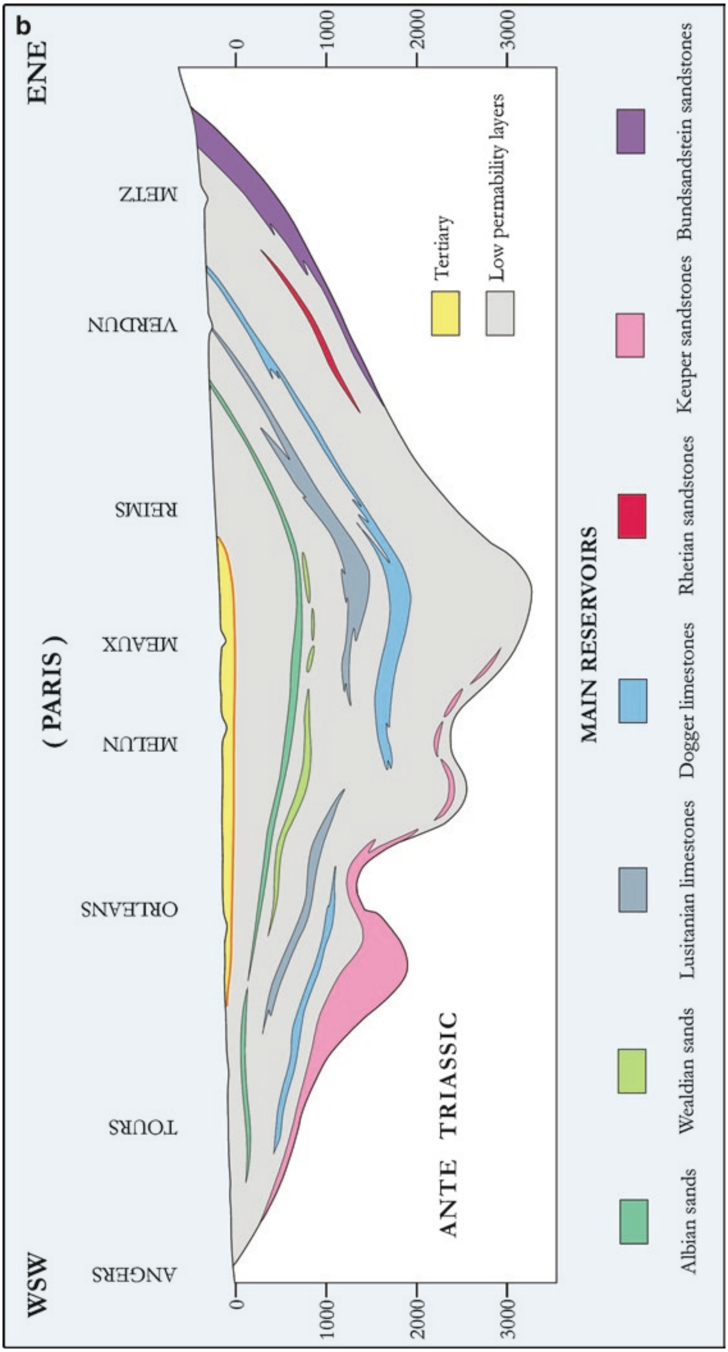

Fig. 6 (continued) Panel **b**. Main reservoirs identified in the Paris Basin

The METSTOR (Méthodologie de présélection des sites de stockage du CO_2 dans les réservoirs souterrains en France (Site preselection methodology for CO_2 storage in subsurface reservoirs in France)) project involves most of the institutions that participated in the GESTCO project. The project estimated the total CO_2 disposal capacities of the entire aquifer at 15.5 Gt for the Trias reservoir (Bundsandstein and Keuper reservoirs) and 13.6 Gt for the Dogger reservoir (Bonijoly et al. 2009). These estimates correspond to 'effective' or 'realistic' capacities that assume realistic reservoir behaviour, as opposed to 'theoretical' capacities that would comprise the entire porous volume accessible to CO_2, fluid saturation and maximum adsorption available in coal.

The earlier capacity estimates of the GESTCO project (22 Gt for Trias and 4.3 Gt for Dogger) corresponded to the theoretical capacities. They also provided the effective capacities, by applying a coefficient that represents the ratio of the disposal capacity of the aquifer confined in traps to the capacity of the entire aquifer: 3% was assumed for the Trias reservoir, and 0.2% for the Dogger reservoir (Bonijoly et al. 2003). A confined structure facilitates the monitoring of injected CO_2, as it is retained in defined areas and reservoir models can be constructed with a higher degree of certainty than in unconfined aquifers (Bentham and Kirby 2005). It should be noted that there is a significant difference between the estimates made by the GESTCO project and those of the METSTOR project. However, no new discussion on this point has been made under the METSTOR project.

In 2008 Veolia launched a CCD project. Claye-Souilly near Paris was selected as the site for a pilot plant. The plant will handle 200,000 t CO_2/year. The gas will be injected into a saline aquifer at a depth of more than 1,500 m for several years (Veolia Environment 2008). Building on previous preliminary evaluation studies of the Paris Basin for CO_2 disposal in depleted hydrocarbon fields and deep saline aquifers, the PICOREF project narrowed the list of potential sites for a pilot injection project to areas about 120 km south-east of Paris, where the roof of the Dogger reservoir is located at a depth of about 1,500 m (Durst and Kervevan 2007).

CO_2 disposal capacity in hydrocarbon fields in the Paris Basin (oilfields) and the Aquitaine Basin (oil- and gasfields) was roughly estimated using static-equilibrium assumptions, implying that the estimates may be conservative. For oilfields in the Paris Basin, it was estimated at 100 Mt CO_2 (with a minimum and maximum of 83 Mt and 117 Mt). For oil- and gasfields in the Aquitaine Basin, it was estimated at 283 Mt (with a minimum and maximum of 140 Mt and 327 Mt), and at 277 Mt (with a minimum and maximum of 170 Mt and 383 Mt), respectively (Brosse 2009). The south-eastern part of the Paris Basin has been thoroughly explored by oil and gas companies. In this area, several oilfields are located either in the uppermost limestone formation of the Dogger Group or in the sand-rich units of the Keuper Group. The data for carbonate reservoirs of the Saint-Martin-de-Bossenay oilfield were made available to the PICOREF project by an operating company (Brosse et al. 2006).

In the Lacq basin (part of the Aquitaine Basin) in south-western France, the company Total launched a CO_2 capture and disposal project (Total 2007). The injection site is the depleted gasfield at Rousse near Chapelle de Rousse. The reservoir lies 4,500 m below the surface and is about 2 km long. It is part of the Adour-Arzaq sub-basin, which is one of four sub-basins of the Aquitaine Basin (Gapillou et al. 2009). The plan is to inject 150,000 t CO_2 during the first 2 years of the project. The selection of the site was made as a result of preliminary studies on all depleted fields operated by Total in the region (the studies were not published).

The METSTOR project provided the first estimates of the theoretical capacities for CO_2 disposal in coalbeds in southern France (Bonijoly et al. 2009). The assessment was limited to 100 km^2 of an unexploited area of the Gardanne coal deposit (near Marseille), which is located at a depth of 500–1,500 m. The result was an estimated theoretical capacity of CO_2 storage of 70 Mt.

3.1.4 Implementation Issues

At present, there is no comprehensive regulatory framework for the geological disposal of CO_2 in France. The PICOREF project included a review of the current regulatory environment (Blanchard 2006), including the mining code (incorporating the waste act, the water act, environmental protection and liability for damage resulting from mining), the environmental code (legislation on industrial facilities, environmental impact assessment, waste management, protection of groundwater and surface water) and the regulation for underground gas storage.

The GESTCO project discussed the potential for simultaneous processes of geothermal operation and injection of CO_2, either in dissolved or supercritical form (Bonijoly et al. 2003). The technically and economically most acceptable scenario for the injection of CO_2 in dissolved form is based on an injection rate of 36 t/day for an average geothermal injection flow rate of 150 m^3/h. The injection cost for this operation is estimated at €100/t CO_2 injected. The injection of CO_2 in supercritical form has the advantages of larger quantities of CO_2 (up to 500 t/day per well) and lower injection costs (€15.6/t CO_2). However, the latter requires preliminary processing and transport of CO_2 to the injection sites, while the risk of a vertical leakage of supercritical CO_2 through the caprock is not negligible. The estimated investment cost for the dissolved form injection is €4 million and for the supercritical form injection about €4.3 million per site.

The first CO_2 injection in France will most likely be the above-mentioned CCD project by Total. The authorization for the injection project for a maximum of 120,000 t CO_2 was granted in May 2009 (Préfecture des Pyrénées-Atlantiques 2009). The injection was planned to commence in June 2009 (Carbon Capture Journal 2009). The total cost of the project, including construction of a unit to extract oxygen from the air and a compression plant for the CO_2, provision of new boiler burners, the modifications to the boiler to enable combustion in the presence of pure oxygen (at the capture site), the work-over of the injection well, the installation of a new unit to compress the CO_2 before injection (at the storage site) and the operating expenses for 2 years are estimated to be about €60 million (equivalent to a total system of cost of €500/t CO_2). Although CO_2will be transported for 27 km from the capture site to the injection site, no extra investment is needed for transportation facilities, as an existing gas pipeline will be utilized as a dedicated CO_2 pipeline. The capture and transport phases of the project will be carried out in accordance with the existing regulatory framework for Environmental Protection at Industrial Sites and Pipeline Transport of Mineral Resources. The injection phase is covered by existing petroleum regulations, as injection will take place on an existing gas production permit. The results of Total's project are expected to provide the authorities with data to help draft appropriate legislation tailored for larger-scale future CCD projects (Total 2007).

The company Total has made outreach and information efforts, notably through the Local Commission for Information and Monitoring (la Commission locale d'information et de surveillance (CLIS)) of the Pyrénées-Atlantiques prefecture. A public opinion survey conducted in 2007 among 1,076 respondents showed that the French public was not strictly opposed to CCD, but was more suspicious than supportive. CCD is simply not known to the public. Only 6% of the respondents were able to define it (Ha-Duong et al. 2009).

3.2 Sources of Radioactive Waste and Geological Disposal in France: Status and Issues

3.2.1 Nuclear Installations and Waste Generation

In 2008, 59 nuclear power plants were operating in France which generated 418 TWh of electricity, 76% of the total electricity generated (IAEA 2009). All SF from reactor operation is being reprocessed at a plant at La Hague in the Basse-Normandie region. The reprocessing plant includes waste processing facilities for treatment and conditioning, and storage areas. An earlier reprocessing plant at Marcoule in the Languedoc-Roussillon region is currently under decommissioning (IAEA 2008).

The National Radioactive Waste Management Agency (Agence nationale pour la gestion des déchets radioactifs (ANDRA)) is mandated by the Planning Act of 2006 (see Sect. 3.2.2) to publish an RW inventory every 3 years. According to the latest report (ANDRA 2009), the reprocessing plants had produced 2,208 m^3 of HLW by the end of 2007, all of which were in storage (1,650 m^3 at la Hague and 558 m^3 at Marcoule). A small fraction (74 m^3) of these volumes consists of HLW from various research activities carried out by the French Atomic Energy Commission (CEA). In addition, 11 m^3 of vitrified HLW packages produced in the PIVER (standing in English for 'first industrial pilot plant for the vitrification of solutions of fission products') pilot plant before 1980 are stored at Marcoule. Some 54.5 m^3 are stored in Cadarache in the Provence-Alpes-Côte d'Azur region and 19.5 m^3 are stored in Saclay in the Île-de-France region.

ANDRA (2009) also provides estimates of the expected volumes of RW for 2020, 2030 and after 2030 (Table 6). The volumes are based on the following assumptions: the existing 58 NPPs (one plant was closed during 2009) and one new European Pressurized Reactor (starting from 2013) operate until each NPP reaches

Table 6 Expected volume of high-level waste in France

	2007	2020	2030	2030–2055
Total HLW (m^3)	2,293	3,679	5,060	7,910
of which: spent fuel	74	74	74	74
of which: PIVER	11	11	11	11

Source: ANDRA 2009
PIVER: Vitrification pilot plant (premier pilote industriel de vitrification de solutions de produits de fission)

the end of its plant life of 40 years; annual power output is assumed to be 430 TWh/year (plus 13 TWh from 2013 onward); and all SF are reprocessed, with reprocessing of MOX fuel starting in 2031.

3.2.2 Geological Formations for Radioactive Waste Disposal

In 1991 the Act on Research on Radioactive Waste Management (the so-called Bataille Act) was adopted. Article 4 stipulates the directions for research on geological disposal of HLW. Article 4 specifies that: (1) the Government shall submit to Parliament a report on the progress of research on HLW management, in which, among other things, the possibilities of reversible or irreversible disposal in geological formations shall be explored through the implementation of underground laboratories; and (2) within 15 years the Government will submit to Parliament a comprehensive report evaluating the establishment of an HLW disposal facility, together with a bill on the establishment of an HLW storage centre. The Act prohibits the storage or disposal of RW in these laboratories.

Among 30 sites nominated as potential locations for a laboratory, a few sites were identified as a result of a mediation mission (mediation mission on the establishment of underground research laboratories) (Bataille 1994), in which geological feasibility criteria and expressions of interests from local communities were taken into account. The geological criteria for the implementation of underground laboratories are: (1) rock with very weak permeability with sufficient volume and at sufficient depth; (2) geological stability at a depth over 200–300 m; (3) a depth of under 1,000 m for safe operation of facilities; and (d) non-occurrence of natural resources at the site. The first two are considered particularly important.

The area straddling the Haute-Marne and the Meuse sites (later referred to as Bure) is characterized by a layer of clay of 130 m thickness at 400 m below the surface. The site of Gard near Marcoule is characterized by a layer of clay over 300 m in thickness. The site is close to a fault zone, and therefore seismic risks are present. The site of Vienne (later referred to as la Chapelle-Bâton) is characterized by a granite massif (Bataille 1996). The review by the Nuclear Installation Safety Directorate (DSIN) prioritized the sites in the order of Bure, Gard and le Chapelle-Baton, while technical reservations against la Chapelle-Bâton were noted (Bataille and Galley 1998). Bure was then selected as the location for the laboratory. An in situ experimental chamber became operational at the end of November 2004. It is located in a layer of Callovo-Oxfordian clay, with a thickness between 100 m in the south-west and 160 m in the north-west, at an average depth of about 450 m and with a surface area of around 100 km^2 (Bataille and Birraux 2005).

In 2005, 15 years after the 1991 Act, the reports and the bill stipulated by the Act were submitted to the Parliament. ANDRA submitted two reports on two types of geological formation, one on clay (ANDRA 2005a) and the other on granite (ANDRA 2005b), for deep geological disposal of HLW. Both types of geological formation were assessed positively.

According to the above-mentioned study on clay by ANDRA (2005a), the clay layer of Callovo-Oxfordian is argillite (i.e. the formation is made up of 40–45% clay minerals, with the rest being other minerals, mainly quartz and carbonates). It is a sedimentary rock with very little permeability, and elements dissolved in water move only very slowly because their migration results mainly from their own movement rather than from being driven by water circulation. It has a chemical environment that enables absorption of chemical disturbances. Furthermore, the argillite has good mechanical strength while being sufficiently deformable to adapt to long-term movements that occur very slowly over time. When the actual site is being selected, the geological environment must be very stable over a long period, without exposure to earthquakes and erosion. The rock must be homogeneous in terms of its structure and mineral composition, and it should have stable chemical properties. It should also be drillable.

The ANDRA study (ANDRA 2005b) on granite referred to above indicates that granite also presents some favourable properties for HLW disposal: it is hard, strong, slightly porous, and shows very low permeability and good thermal conductivity. Most of the massive granite in France reaches significant depths, offering great flexibility for disposal design. Any changes in the composition of the rock from one point to another of the mass do not significantly alter its properties. However, up to a few tens of metres, small fractures can affect the local permeability of the rock. Faults that can reach several kilometres are far less numerous. In the actual implementation of the disposal facility, the identification of granite blocks without fault is a major issue. Nonetheless, priority is given to clay for further development in France.

In June 2006, based on the reports, the Parliament adopted the Planning Act on the sustainable management of radioactive materials and waste, which stipulates that studies on reversible disposal in deep geological formations are to be pursued, so that an application for authorization can be filed by 2015, with operation of the disposal facility from 2025 (OECD 2009).

3.2.3 Locations and Capacity Estimates

The research by ANDRA on the clay formations confirmed favourable site-specific conditions at the Meuse/Haute-Marne area, whereas for the granite the main uncertainty concerns the existence of sites without 'too many faults' in the granite massifs, as they would be exceedingly dependent on engineered barriers. The area with clay formation north-west of the Meuse/Haute-Marne laboratory with a size of

200 km^2 was defined as a transposition zone, which has equivalent geological properties to the laboratory site. The exact location of the disposal site could be decided by 2013. A basic design for the architecture of the disposal facility is proposed by the same study. It adopts the modular approach, which allows gradual construction, operation and closure within each zone.

The overall capacity of potential geological disposal sites in France is clearly much larger than any existing and foreseeable amounts of RW generated in the country. In other words, capacity constraint for geological disposal of RW is not an issue. Thus, the capacity of the geological repository to be developed will be determined by need (i.e. the cumulative amount of RW produced in France).

3.2.4 Implementation Issues

Public consultation and dialogue with the local population is an important issue in France. There was a 1 year moratorium for the site selection process for underground research laboratories in 1990. This was in response to strong local opposition to the research initiated by ANDRA on HLW that aimed to study the possibility of implementing laboratory research in four *départements* between 1988 and 1989. The opposition was due to the proceedings having insufficient prior information and no legal guarantees (Bataille 1994). In response, more importance was attached to local consultations thereafter. In 1991 the Bataille Act set out a procedure for public consultations in the search for the underground laboratory, and mandated dialogue with the local population before undertaking any preliminary exploration work for a site.

The Planning Act in 2006 defined procedures for implementation of a deep geological disposal facility. It stipulated that application for a repository licence be reviewed in 2015 and that (subject to granting of the licence) the repository be commissioned by 2025. The application must relate only to a geological formation that has been investigated through an underground laboratory, and the facility must guarantee the reversibility for at least 100 years. The Act further defined a public consultation process, including an obligation for public debate at specified milestones (Article 12), the formation of public interest group (Article 13), and the establishment of a local information and oversight committee for monitoring research activities at the underground laboratory (Article 18). The Act also established a fund to finance the construction, operation, termination, maintenance and monitoring of the facility, together with a committee to oversee its financing.

In 2004–2005, the French Government, ANDRA and waste producers (Eléctricité de France (EDF), AREVA and CEA) conducted a joint study to estimate the cost of deep geological disposal of HLW in clay formations (DGEMP 2005). In the baseline case (industry scenario) the total costs are estimated in the range of €13.5–16.5 billion. These cost estimates are given jointly for HLW and long-lived ILW, and their volumes correspond to those generated throughout the lifetime (assumed to be 40 years) of the current 58 NPPs. The latest cost estimates by

ANDRA are cited in the same report, showing that costs estimated for long-lived ILW alone are about 10% of total costs. The estimate is based on a scenario in which reprocessing of all SF is assumed.

3.3 Comparison of Geological Disposal of CO_2 and Radioactive Waste in France

This section provides a concise comparison of the geological disposal of CO_2 and RW in France. The main points are summarized in Table 7.

Research on CO_2 disposal in France has reached a stage where three major pilot projects are presently under preparation. The research has been advanced mainly through the participation of French research institutions in EU projects on CCD. The assessment of geological formations in France has been focused on the Paris Basin because of its close proximity to the largest emission sources. To date, no comprehensive regulatory framework exists for CO_2 disposal in France.

In contrast to the CCD activities, the research on the disposal of HLW has been strongly guided by laws. A candidate site for a repository was narrowed down to a 200 km^2 transposition zone. Site selection is primarily guided by the interest expressed by local governments in hosting a repository, as the law mandates consultation with local authorities prior to preliminary studies. Proximity to waste generation sources is not an important factor in the site selection process, presumably because there are only three sites in France where HLW is being generated.

France produced approximately 0.4 Gt CO_2 in 2005. Geological CO_2 disposal capacity in France is estimated at about 30 Gt, a technical estimate that does not consider socio-economic and regulatory constraints on disposal potential or trapping efficiency. The potential for geological disposal of RW is much larger than the cumulative amounts of RW generated to date and projected over the next few decades. Moreover, the law mandates commissioning of a single repository. Thus, its capacity is basically determined by the amount of RW generated. The volume of HLW is expected to amount to approximately 5,000 m^3 by 2030.

Favourable geological conditions for CO_2 disposal include permeable rocks covered by impermeable rocks. Impermeable rock is a favourable condition for RW disposal, and geological assessments aimed at selecting possible CO_2 sites benefit from geological knowledge obtained through the search for RW disposal sites. Aquifers in the Paris Basin, in particular, the Bundsandstein, Keuper and Dogger layers, are assessed to have favourable geological conditions and sufficient capacities for CO_2 disposal, whereas the argillite formation of the Callovo-Oxfordian layer is a target formation for RW disposal. As far as the depth of the disposal is concerned, geological formations deeper than 1,000 m are targeted for CO_2 disposal, whereas formations of less than 1,000 m are targeted for the disposal of HLW.

During the search for a potential site for an underground research laboratory for RW in the late 1980s, local opposition led to the termination of research at several

Table 7 Comparison of geological disposal of CO_2 and nuclear waste in France

Criteria	Carbon dioxide	Radioactive waste
Geological environment considered for disposal	Permeable rock more than 1,000 m deep	Little permeability
	An impermeable cover to ensure storage security	Geological stability at a depth of at least 200–300 m, but less than 1,000 m for safe operation
	A stable structure (i.e. trap) to limit lateral transfers	
Rock type and characteristics	Aquifer reservoir (sandstone, conglomerate, oolitic limestone etc.)	Argillite (sedimentary rock)
	Hydrocarbon deposits	Granite
	Coalbeds	
	Basic and ultrabasic formations	
Mode and purpose of disposal	Injection of CO_2 in dissolved form into the geothermal water, or injection into the supercritical form	Emplacement in engineered galleries
Volume (disposal capacity)	29.1 Gt in the Paris Basin aquifer, unconfined;	The amount of radioactive waste is very small compared to the potential geological disposal capacity
	393–827 Mt in hydrocarbon deposits;	
	70 Mt in coalbeds	
Depth	Maximum depth of 1,800 m (Bundsandstein aquifer), 2,800 m (Keuper aquifers), 1,100–1,800 m (Dogger aquifer), >1,500 m (Veolia project)	Average depth of 450 m (Callovo-Oxfordian formation at Bure)
Containment mode	Natural barriers with very low permeability	Combination of natural and engineered barriers with very low permeability
Site selection and public acceptance	An area for a government-led CO_2 injection pilot project has been defined, and its geological characteristics studied.	The underground laboratory at Bure opened in 2004
	Two CCD projects led by multinational companies (Total and Veolia) initiated	Public opposition was strong in some candidate areas for the underground laboratory
	CCD is not yet well known by the public	The area and target geological formation for the repository have been selected and studied
Implementation issues	No regulatory framework exists, but it is expected soon following the recent EU directive on CCD	The Planning Act was adopted in 2006. It defines the implementation schedule. Some costing studies exist
	Injection costs for the current pilot projects range between €15 and 100. Total CCD system costs including transport for the first pilot project are as high as €500/t CO_2	

sites. This was because procedures did not allow for a sufficient level of local consultations. In 1991 a law was passed mandating local consultations when researching sites for underground research laboratories. A 2006 law likewise stipulated the procedure for public consultation in selecting the site for a final repository. Research into CO_2 disposal is much more recent than into RW disposal. A recent public opinion survey shows that CCD is not widely known about by the public.

Detailed costing studies for CO_2 disposal in France are not available. There are rough cost estimates of about €60 million provided by the company Total for its 120,000 t CCD project at Lacq. Estimates of CO_2 injection costs consisting only of investment and operation of an injection well in the case of simultaneous operation of CO_2 injection and geothermal energy production are available. When the CO_2 is injected in a dissolved form into the geothermal water, the investment and operation costs are estimated at €4 million or €100/t CO_2 (with disposal rates of up to 36 t/day). If CO_2 is injected in a supercritical form, the cost estimates are €4.3 million total or €15.6/t CO_2 (with a disposal rate of up to 500 t/day). However, these estimates do not include the costs of the necessary preliminary processing and transport of CO_2. For RW, ANDRA and other companies have published cost estimates which are in the range of €13.5–16.5 billion for handling the cumulative amounts of HLW and long-lived ILW over the complete lifetime of all previously existing and present NPPs.

4 United Kingdom

4.1 CO_2 Sources and Geological Disposal in the UK: Status and Issues

4.1.1 Fossil-Based Electricity and CO_2 Emissions

The UK emits more than 500 Mt CO_2 every year. GHG emissions have increased, and reached an estimated 640 Mt CO_2-eq. in 2007. The most important GHG is CO_2, which accounts for 85% or 544 Mt (Defra 2008). Fossil fuel-based power plants are the main sources of CO_2, but steel plants, refineries and the petrochemicals sector also contribute significantly to GHG emissions. Most of the 50 largest CO_2 sources are concentrated in the southern part of the UK (see Fig. 7). These comprise 37 combined heat and power plants, 8 refineries, 3 integrated steel plants, a chemical plant and a cement plant (Holloway et al. 2006).

In 2004, 61% of total CO_2 emissions in the UK originated from fossil fuel power plants. Fitting CCD equipment to the 20 largest power plants in the UK would reduce total CO_2 emissions by approximately 20% (Holloway et al. 2006). CCD can reduce the emissions of a typical fossil-fired power plant by roughly 90% (DECC 2009a). The Government has taken steps to promote this technology and has announced the target of making CCD commercially viable by 2020 (DECC 2009b). In April 2009, the UK Government took new measures to encourage CCD

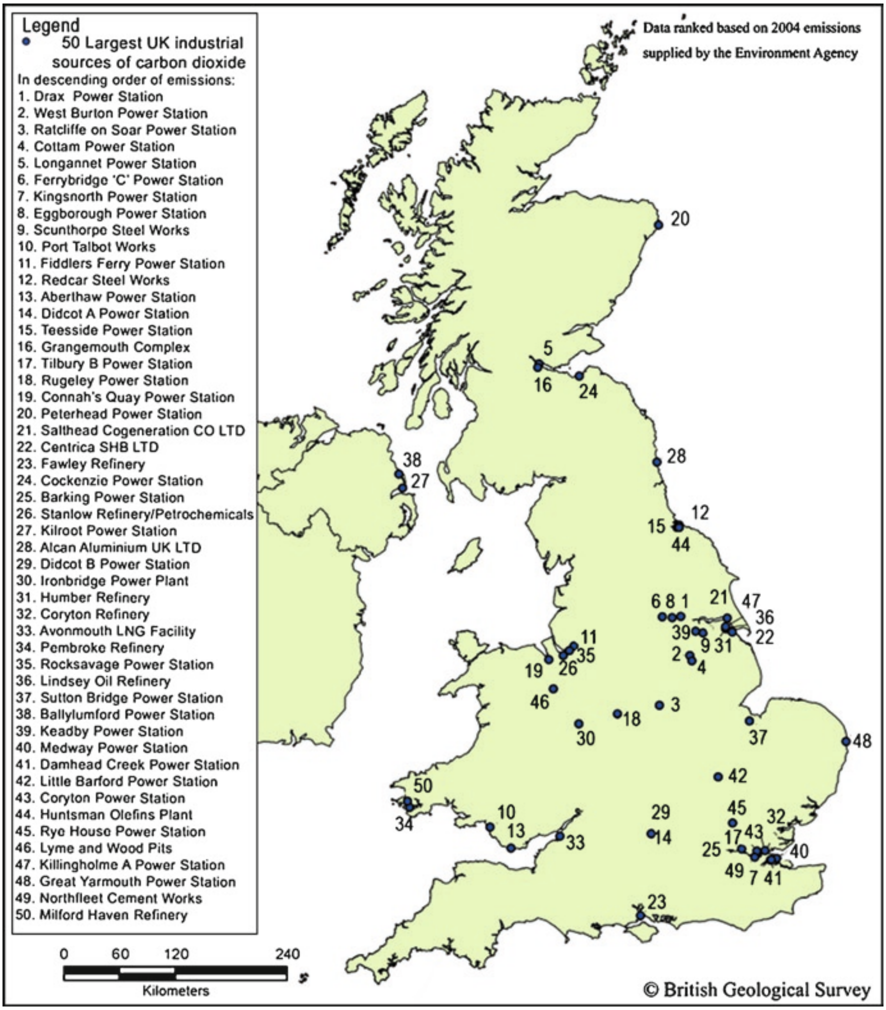

Fig. 7 The largest industrial sources of CO_2 in the UK (Source: Holloway et al. 2006)

development, and confirmed a 'no new coal without CCD' policy. Any new combustion power plant in excess of 300 MW (net output), regardless of whether it is running on gas, coal, oil or biomass, would have to be built with carbon capture ready technology. Five years after the technology is proven to be commercially ready, a full-scale retrofit of CCD will be required (DECC 2009a).

The UK has committed to national and European CO_2 reduction targets: the EU targets to reduce GHG emissions by 20% from 1990 to 2020 (DECC 2009c) and by 80% from 1990 to 2050, as well as the legally binding targets of the UK Climate Change Act 2008 that require UK CO_2 emissions to be reduced by 26% from 1990 to 2020 (UK Parliament 2008). In 2007 the Government launched a competition for construction of the world's first commercial-scale CCD power plant in the UK (capturing CO_2 from a coal-fired power plant of 300 MW net capacity and with offshore CO_2 disposal). In June 2009, the Government proposed a new financial and regulatory framework to assist with the development and delivery by establishing an Office of Carbon Capture and Storage within the Department of Energy and Climate Change (DECC 2009c). The UK Low Carbon Transition Plan released in July 2009 (DECC 2009c) and the UK Low Carbon Industrial Strategy (BIS and DECC 2009) aim to promote CCD in the power sector.

4.1.2 Geological Formations for CO_2 Disposal

In the case of the UK, geological formations considered suitable for long-term geological disposal of CO_2 are oil- and gasfields, as well as saline aquifers (i.e. saline water-bearing reservoir rocks). EGR and EOR technologies are expected to bring additional economic benefits to CO_2 disposal projects, given the long experience with such technologies and the large amount of data available.

The quantifiable CO_2 disposal potential in coal seams in the UK is considered small because of low permeability, which makes unmineable coal seams a less viable option. There are significant coal resources in the UK at depths greater than 1,500 m, but their permeability is expected to be even lower than the seams located at shallow depths (Jones et al. 2004). Conflict of use between CO_2 disposal and future coal extraction has been emphasized. Moreover, knowledge about CO_2 disposal in deep coal seams is limited, especially in view of uncertainties regarding the diffusion of CO_2 into the coal above the critical temperature of 31.1°C. This makes coal seams a less likely option for CO_2 disposal in the foreseeable future.

4.1.3 Locations and Capacity Estimates

Following Bradshaw et al. (2007)——and as illustrated in Figure 8——the total CO_2 disposal capacity in the UK can be categorized as: (a) theoretical disposal capacity that consists of a large but speculative capacity or potential, is poorly known or poorly constrained, and includes uneconomic opportunities; (b) realistic disposal capacity that meets both geological (permeability, porosity, heterogeneity) and engineering criteria and is estimated using existing basin data; and (c) viable capacity, which is built upon realistic estimates and considers various additional economic, legal or regulatory issues regarding CO_2 disposal. If not otherwise stated, capacity estimates in this section refer to the theoretical capacity.

Disposal of CO_2 in the offshore sedimentary basins that contain most of the UK oil- and gasfields is considered the most relevant option (Holloway et al. 2006). The capacity of onshore oil- and gasfields in the UK is considered too small, and major aquifers are widely used for potable water extraction. Formations that trap gas and oil are quite extensive and many of them are considered suitable for CO_2 disposal. Generally, major basins have been identified for potential CO_2 disposal, including the southern North Sea Basin (gas), the central and northern North Sea Basins (oil and

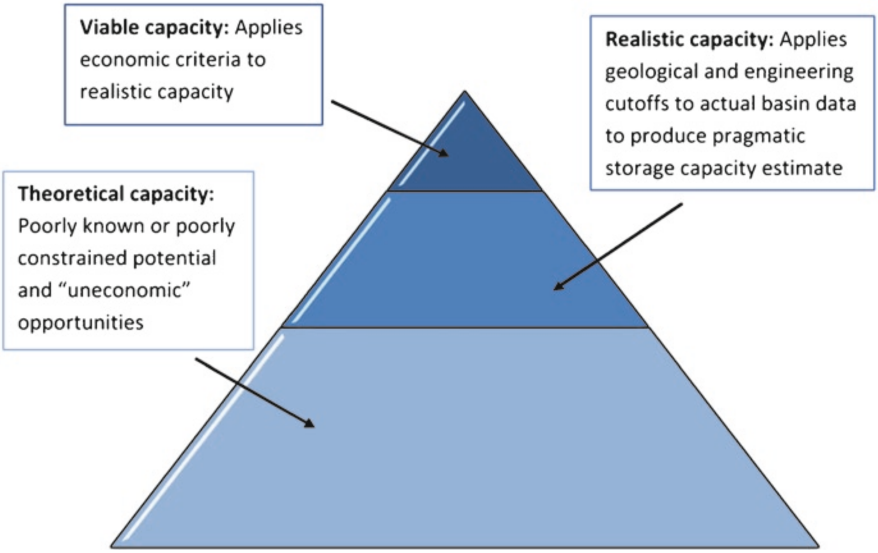

Fig. 8 Techno-economic resource pyramid for geological CO_2 storage space (Adapted from Bradshaw et al. 2006)

gas) and the Irish Sea (gas). In the case of saline aquifers, the potential disposal sites are the southern North Sea gasfields. Figure. 9 shows the locations of the offshore hydrocarbon fields and the major oil-bearing and gas-bearing sedimentary basins.

A recent study by the Scottish Centre for Carbon Storage (SCCS 2009) includes a comprehensive assessment to identify the potential disposal sites for CO_2 in Scotland and north-eastern England. Most of the potential CO_2 disposal sites lie in offshore saline aquifers, as well as in a few depleted hydrocarbon fields. The study identified 29 potential hydrocarbon fields for CO_2 disposal. Amongst these fields, the most promising disposal sites are four gas condensate fields (the Brae North, Brae East, Britannia and Bruce fields), a gasfield (the Frigg Field, UK) and an oilfield (the Brent Field), with an estimated total CO_2 disposal capacity of between 300 and 1,000 Mt.

Unlike hydrocarbon reservoirs, detailed information about saline aquifers beneath the North Sea is not readily available. Therefore, a generic figure of disposal efficiency was estimated (SCCS 2009) based on other regional studies and numerical models, using a disposal efficiency between 0.2 and 2% of pore volume, which implies a total CO_2 disposal capacity of 4,603–46,012 Mt. The study (SCCS 2009) also identified ten saline aquifers that meet the geological and disposal requirements. The analysis showed that the oil- and gasfields pose a low risk and lowest cost options and are thus more promising than saline aquifers. Without EOR, oilfields offer only limited capacity, mainly because of the past replacement of extracted oil with water for pressure support. Thus, the depleted gas and gas condensate fields show the best prospects for CO_2 disposal.

The UK, in a collaborative effort with the Government of Norway, also participates in the monitoring programme of Statoil Hydro in the Sleipner field, the

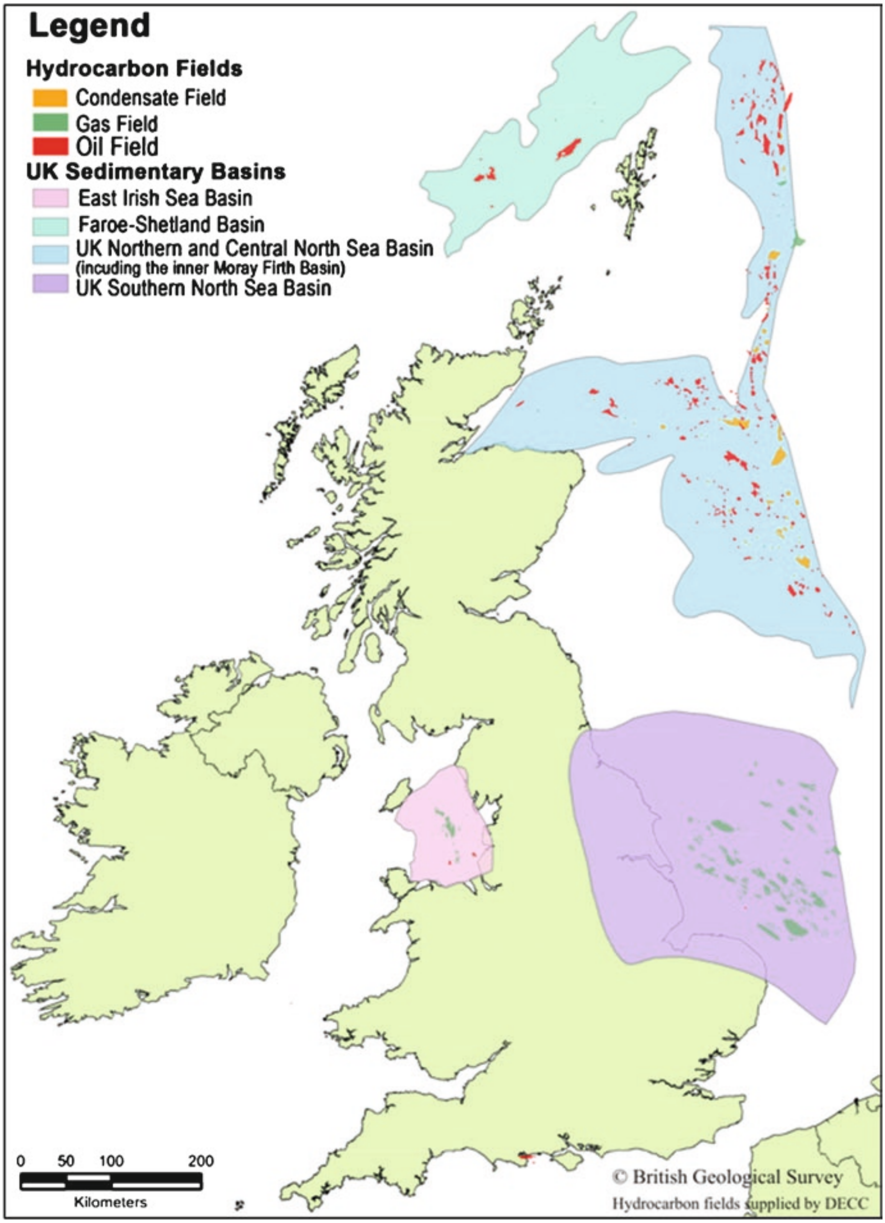

Fig. 9 Offshore hydrocarbon fields and the major oil- and gas-bearing sedimentary basins (Source: Holloway et al. 2006) (*see* Colour Plates)

world's first commercial CO_2 disposal project. Statoil Hydro also plans to establish a full-scale CCD project at the Mongstad refinery in the future. In 2008 a second CCD project at Snohvit was initiated by Statoil Hydro. The UK and Norway are also working to draft regulations for transport of CO_2 in the North Sea (DECC 2009c).

Table 8 Theoretical estimates of the gross CO_2 disposal capacity in the UK

Type of disposal	Potential CO_2 capacity
Gas and condensate fields	5,982 Mt (75 fields)
Oilfields	4,225 Mt (74 fields)
Saline aquifers	14,446 Mt (32 sites)

Source: ACCAT 2009

In the UK the total theoretical gross capacity for CO_2 disposal is estimated at 24.7 Gt (BERR 2007). Table 8 shows the breakdown of the total gross capacity, although the estimate is speculative and theoretical. Such potential is likely to be much smaller when socio-economic factors have been taken into account (ACCAT 2009).

Nevertheless, it is believed that these numbers are initial estimates with large uncertainties which require further testing against empirical data. Further validation and verification are required, especially as 60% of the capacity is associated with saline formations for which data quality is considerably poorer than for oil and gas reservoirs and coal seams. Disposal in such geological formations requires a combination of a porous and permeable reservoir rock that will act as the disposal reservoir and an aquitard or aquiclude in a configuration that will isolate the CO_2 from the atmosphere. Only a few studies are available in the public domain that aim to estimate the disposal capacity.

4.1.4 Implementation Issues

Public response to the use of CCD in the UK has been generally favourable because it is seen as allowing increased energy production without an increase in CO_2 emissions. However, this may be because there has not yet been a real public debate about the subject and because all suggestions for CCD have only included areas in the UK sector of the North Sea, that is, there is a limited NIMBY (Not In My Backyard) effect. The CO_2 disposal projects in the Sleipner and Snohvit fields in the North Sea have received broad support from the main environmental organizations which may have had a positive effect on the general public's acceptance. Surveys of primary and secondary stakeholder opinion of CCD have been conducted at the EU level by the ACCSEPT project (Shackley et al. 2007) and at the UK level, by the UK Carbon Capture and Storage Consortium (UKCCSC) survey in 2006 (Gough 2008). The ACCSEPT project survey reveals that British respondents were enthusiastic about the role of CCD in reducing carbon emissions, but the UKCCSC survey cited some challenges to CCD, including the lack of long-term policy support, the costs and the requirement for an international regulatory framework. The results from the Fossil Energy Coalition (FENCO) project, which is a comparative study funded by six European governments to study the effectiveness of CCD communication by comparing focus groups and Information-Choice Questionnaire (2009–2010), will be published in 2010 and will shed further light on public perception regarding CCD technology.

As mentioned in Sect. 4.1.1, the UK Government has taken firm measures to implement and develop the CDD technology. These comprise, for example, both the inclusion in the Draft Legislative Programme 2009/10 (OLHC 2009) of the pertinent part of the Energy Bill which proposes financial support for four CDD demonstration plants, as well as the establishment by DECC of an office responsible for CCD-related matters to assist with the implementation process.

The UK Government is also working with other organizations to develop a long-term stable regulatory strategy. For example, it works with the OSPAR Commission (OSPAR Commission for the Protection of the Marine Environment of the North East Atlantic) to provide a legal basis for CCD that requires an amendment to the London Protocol (1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972) to allow for sub-seabed CO_2 disposal. The Government proposed amendments to the EU Emissions Trading System (ETS) Directive regarding CCD (UK Parliament 2008), and it is working with EU partners on a potential agreement to use allowances from the EU ETS to support 12 CCD demonstration projects by 2012. The Government agreed with G8 leaders in July 2008 to support 20 large-scale CCD demonstration projects by 2020. It was involved in the development of the EU–China Near Zero Emissions Coal Initiative for a commercial-scale CCD demonstration project in China; it also co-hosted (with Norway) the Carbon Sequestration Leadership Forum Ministerial Meeting in October 2009 (DECC 2009c).

The potential economic benefits of CCD due to EOR and EGR depend on the oil price and, to some extent, on the price of CO_2 in the European market. Some initial estimates by the Scottish study (SCCS 2009) carried out recently showed that CO_2 EOR may be economical in North Sea oilfields at an oil price of US$80–110 per barrel, depending on whether the cost of CO_2 (US $28–56 per tonne) is included in the project cost. If risk premiums are included, then it is unlikely that CO_2 EOR will be commercially viable in North Sea fields at an oil price of less than US$100 per barrel. As offshore CO_2 EOR has not been applied in the early projects, it implies significant financial risks, as detailed engineering design and economic appraisals will require full risk assessments. Other important findings of the study are: the financial cost of initiating CCD will be high but comparable with costs of commercial renewable energy sources; the levelized costs of CCD gas and CCD coal are similar; and the carbon prices have to be high and stable over the long term for the financial viability of large-scale CCD.

4.2 Sources of Radioactive Waste and Geological Disposal in the UK: Status and Issues

4.2.1 Nuclear Installations and Waste Generation

In 2006, 19% of the UK's electricity was generated by NPPs. This share dropped to 15% or 57.5 TWh in 2007 and further declined to 13.5% or 52.5 TWh in 2008 (WNA 2009b). At present, the UK has 19 operating reactors (IAEA 2009), 18 of which are expected to be retired by 2023. The NPPs are spread over ten different sites around the country with 14 advanced gas-cooled reactors (AGRs), four magnesium non-oxidizing (Magnox) reactors, and one pressurized water reactor (PWR). The UK expects to bring online a new generation of NPPs, at the very earliest by 2017. Against the background of energy security and the Government's ambitious target (announced in 2008) to reduce GHG emissions by 80% by the year 2050, the UK Government's position has recently become favourable to nuclear power (Summers and Carrington 2008).

The main sources of RW in the UK are NPPs and the activities related to the fuel cycle (Figure 10). Other sources are industry, medical applications and research. To review options for long-term storage and disposal of HLW, the Government established a representative committee in 2003: the Committee on Radioactive Waste Management (CoRWM). In 2006, after 3 years of research, the CoRWM recommended the solution of deep geological disposal for long-lived HLW and ILW and 'robust interim storage' (Defra et al. 2008). In October 2007, a new CoRWM was announced which was given the task of reporting on progress in the geological disposal of RW.

The Nuclear Decommissioning Authority (NDA) has the task of managing this long-lived waste and of developing a suitable geological disposal facility (GDF). The UK Government has mandated the NDA with planning and delivering the GDF, which is to be 'a safe, environmentally sound, publicly acceptable geological disposal solution' for this waste (NDA 2007). As part of the process, the NDA will reach out to and engage the regulators, stakeholders and relevant communities (Defra et al. 2008). Eventually, it is expected that the Radioactive Waste Management Division (RWMD) of the NDA will develop into a Site Licence Company that will be responsible for construction and operation of the GDF and will be known as a 'delivery organisation'. The NDA will also develop a Disposal System Specification that will support the GDF implementation programme (NDA 2009a).

4.2.2 Geological Formations for Radioactive Waste Disposal

Geological Formations

Suitable and stable rock formations for hosting a GDF for long-lived waste are present in the UK (Defra et al. 2008) and about one third of the said area might be suitable for geological disposal (NDA and Defra 2008). A broad range of generic disposal concepts can be applied to the UK. The White Paper for the NDA (Baldwin et al. 2008) reviewed five geological environments and their applicability to typical rock formations found in the UK (see Table 9).

The geological environments across the UK are highly variable, providing various options for the manner in which a geological disposal facility can be implemented at a suitable site. The study by Baldwin et al. (2008) evaluated a wide range of concepts, with the focus on HLW and SF. For example, disposal in boreholes in evaporate formations with no overpack might be a less expensive option for HLW;

Fig. 10 Locations of major UK radioactive waste producers (Source: Defra 2008) (*see* Colour Plates)

Table 9 Rock formations in the UK that could be considered potentially suitable for hosting a geological disposal facility

Host rock	Overlying rock formation	Relevant geological environment in the study
Crystalline rock	Low-permeability sedimentary rock formations	G1 or G2
Crystalline rock	High-permeability sedimentary rock formations	G1 or G2
Crystalline rock	Crystalline rock to surface	G2
Indurated low-permeability sedimentary rock formation	High-permeability sedimentary rock formations	G3 or G4
Plastic low-permeability sedimentary rock formation	Sedimentary rock formations (permeability unspecified)	G3 or G4
Evaporites——salt dome and bedded salt	Sedimentary rock formations (permeability unspecified)	G3
Carbonate	Sedimentary rock formations(permeability unspecified)	G5

Source: Baldwin et al. 2008
G1: Stronger rocks with very low flow of likely saline waters
G2: Stronger rocks with higher water flow; probably relatively fresh water
G3: Weaker rocks with no effective flow and relatively saline waters in pores
G4: Weaker rocks with very low water flow and relatively saline waters in pores
G5: Evaporite formations: plastic, with no water flow and little accessible water (brine) content

however, SF would require an overpack. Disposal in very deep boreholes seems more suitable for HLW than for SF. Baldwin et al. (2008) suggest that the NDA would need to focus on a subset of more appropriate concepts and develop for one or more site-specific conditions in collaboration with stakeholders. CoRWM (2009a) have also expressed the need to assess a wide range of options.

Geological Disposal Facility

As it will take many years before a GDF is ready to receive waste, the UK Government accepted CoRWM's (2006) recommendation of robust interim storage. The Government issued a White Paper stating: 'The Government considers that waste can and should be stored in safe and secure interim storage facilities until a geological facility becomes available' (BERR 2008). Figure 11 displays an interim storage facility able to prevent hazardous release to the outside environment. The four layers of engineered barriers include: (1) a waste form, which is the primary barrier; (2) the waste container; (3) the control of the store environment, which is the tertiary barrier; and (4) the external store structure, as the final layer of protection. The existing stores for waste packages usually have a service life of 50–100 years. The facility will provide interim storage until the GDF programme is developed. To develop a robust programme for the disposal facility, the NDA is reviewing the existing UK waste storage arrangements, including the Sellafield storage, currently the only storage facility for HLW.

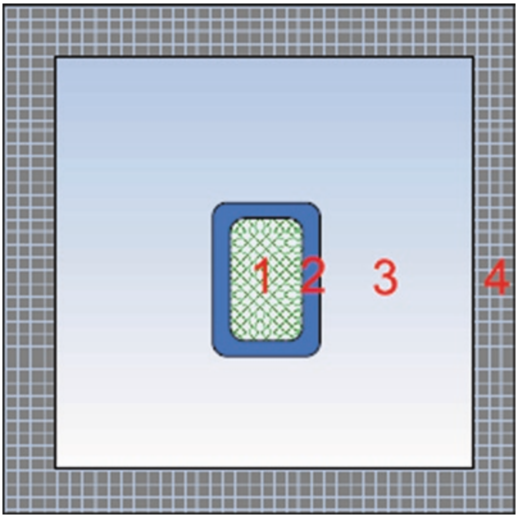

Fig. 11 Interim storage of radioactive waste (Source: Defra et al. 2008) 1: A waste form 2: The waste container 3: Control of the store environment 4: External store structure

Countries like France, Finland, Sweden and the USA have made good progress towards geological disposal. Although no decision has been made in the UK regarding the disposal concept to use, the methodology used in Finland and Sweden is potentially applicable to the HLW and SF in the UK. This involves waste being sealed in copper canisters and put into individual deposition holes that are drilled in the floor of the deposition tunnels. As copper under suitable conditions can be extremely resistant to corrosion, it is expected that in a suitable geochemical environment such canisters could last for a long time and maintain their integrity for hundreds of thousands of years (Defra et al. 2008).

The potential range of depth of the underground areas of a disposal facility for ILW or LLW and HLW/SF would be of the order of 200 m–1 km. However, the exact geological site environment and the design of the disposal facility will depend on the baseline inventory (Defra et al. 2008). Over the coming decades, exchanging experiences and international benchmarking will constitute a key part of the GDF development process in the UK.

4.2.3 Estimates of Waste Volumes and Site Selection for a Geological Disposal Facility

There were no formal plans for geological disposal in the UK between 1997 and 2007. The recent process was initiated following the CoRWM recommendations in July 2006, which proposed geological disposal as a long-term solution for managing HLW. The current target date for an operational GDF for HLW is 2040.

The UK Radioactive Waste Inventory includes three levels of waste: HLW, ILW and LLW. HLW is defined as: ‘wastes in which the temperature may rise significantly as a result of their radioactivity, so that this factor has to be taken into account in designing storage or disposal facilities' (Wilson 1996). It is expected that by 2015, most of the HLW in the UK will have been made 'passively safe' by converting it from a liquid to a solid form using the vitrification process. The treated HLW is poured into stainless steel containers (each with 150 litre capacity) in which the waste will solidify. To significantly reduce its radioactivity through the natural decay process, the vitrified HLW is planned to be stored for at least 50–100 years before final disposal (Defra et al. 2008). At present, all HLW is stored at Sellafield in stainless steel canisters in silos (WNA 2009b).

As of 1 April 2007, the volume of RW in the UK was about 290,000 m^3 (NDA and Defra 2008). The inventory data is updated every 3 years. Table 10 shows the volumes of HLW, ILW and LLW in the UK. The 1,730 m^3 of HLW represent less than 1% of the total volume of RW. On the other hand, 196,000 m^3 of LLW account for 60% of the total volume, but less than 0.1% of the overall radioactivity. The volume of RW is expected to increase in the coming decades and will depend on the quantity and the type of the next generation of NPPs.

It should be noted that reprocessing of SF will not take place for any new reactors, so there is likely to be SF (an estimated volume of 8,150 m^3 based on a variety of assumptions regarding the number of new reactors) as well as HLW in a GDF. However, the bulk of the LLW will not go to a GDF but to a surface-based LLW facility (the estimate for this long-lived LLW is 37,200 m^3) (see CoRWM 2006). It is only some of the longer-lived LLW that will go to a GDF.

Location and Site Selection

The location of the GDF is still not known. The CoRWM report released in March 2009 (CoRWM 2009b) addressed the issue of an interim storage facility, which is the

Table 10 Inventory of high-, intermediate- and low-level waste in the UK

Waste Type	Volume (m^3)	Radioactivity
HLW	1,730	Very high
ILW	92,500	Medium
LLW	196,000	Very low (0.1%)

Source: NDA and Defra 2008

HLW high-level waste, *ILW* intermediate-level waste, *LLW* low-level waste

Note: *Intermediate-level waste (ILW)* in the UK is defined as waste 'with radioactivity levels exceeding the upper boundaries for low-level wastes, but which do not require heating to be taken into account in the design of storage or disposal facilities' (HMSO 1995). ILW is generated mainly from spent nuclear fuel resulting from operations and maintenance at nuclear sites. Typically, ILW is packaged for disposal by encapsulation in cement in highly engineered 500 litre stainless steel *Low-level waste (LLW)* is defined as waste having a content not exceeding 4 gigabecquerels per tonne of alpha activity. The majority of the LLW will go to the LLW disposal facility at Drigg. Only a small volume of the LLW——that containing radionuclides with long half-lives——will go a to a geological disposal facility. In 2008 the estimate for this long-lived LLW was 37,200 m^3. In addition, there is the possibility of civil plutonium and civil uranium being declared as waste. Estimates for these are plutonium: 3,720 m^3 and uranics: 74,950 m^3

first step towards the development of a GDF. This was followed by a report on R&D for interim storage and geological disposal (CoRWM 2009c). This report also highlighted the recent review by the NDA (NDA 2009b) of the UK-wide waste storage options for higher-level waste, including 19 ILW (e.g. at Sellafield, Dounreay, Harwell, Winfrith, Trawsfynydd, Hunterston, Sizewell B, Aldermaston, Amersham and Cardiff) and one HLW store at Sellafield. The NDA review also detailed the plans of the UK nuclear industry for some new storage facilities, such as the plans to construct five new ILW stores at Sellafield, the construction of one new store at Dounreay and British Energy's plan to have one new ILW store at each AGR site. The NDA review process indicated that some of these stores can be 'made fit', after appropriate refurbishment and replacement, to provide safe and secure storage until a GDF is available.

The NDA has developed a Geological Disposal Facility Provisional Implementation Plan (GDF-PIP) and is developing a generic Disposal System Safety Case (CoRWM 2009a). The GDF-PIP assumes that perhaps two potential sites for geological disposal will have been identified by the Government by mid-2012. A GDF is expected to be available from 2040 for ILW and from 2075 for HLW/SF (NDA 2009b), although the NDA recognizes the possibility, highlighted by CoRWM, that a GDF may be delayed beyond this point. Given that the high-activity waste in the interim storage facilities would need to be transported to a GDF, the transport process has to be planned and scheduled very carefully; it is expected that it might take many decades to move all such high-activity waste to a GDF.

At this stage it is not known whether there will be one or perhaps two GDFs. However, the Government has indicated a preference for a single site for all HLW/SF (Defra et al. 2008) and for the concept of a single GDF with two separate parts (one for ILW and long-lived LLW and the other for HLW and SF), also known as a combined or co-located GDF.

Currently no site has been selected but the Government is engaged in a site selection process based on the principles of voluntarism and partnership of local communities. As of autumn 2009 Copeland and Allerdale Borough Councils and Cumbria County Council had submitted expressions of interest in opening discussions with the Government (CoRWM 2009a). A flexible approach is preferred to facilitate and promote confidence among the stakeholders in the project. An important aspect of this approach is the right of withdrawal, which would allow any community to withdraw its involvement in the process (CoRWM 2006). As discussed above, the first step towards a GDF is to define an interim storage facility for a storage period of up to 100 years (CoRWM 2006).

4.2.4 Implementation Issues

Public opinion in the UK has become increasingly favourable towards nuclear power. For example, in a survey carried out in November 2008, 65% agreed that nuclear is needed as part of the UK's energy mix, 44% were of the view that old NPPs should be replaced with new ones, and 40% expected an increased role for nuclear power (WNA 2009b). Among Members of Parliament, support for nuclear power was 72%

in 2008, up from 66% in 2006. In October 2008, Defra initiated a one-day open meeting on the geological disposal of RW to discuss developments in the characterization of deep geological and hydrogeological environments and the potential for geological disposal facilities in the UK (GS 2008). Both the UK Government and the NDA have been involved in public and stakeholder engagements. The UK Government issued a White Paper (Defra et al. 2008) and set up a dedicated website for public information on the topic. The NDA issued consultation documents and organized workshops. However, the Government recognizes that additional efforts will be needed to better inform the public and local authorities (CoRWM 2009a).

The UK has a regulatory regime for the management and storage of RW. Planning and delivering the GDF is a collaborative effort between the NDA and the Government, with the NDA as the implementing organization. In April 2007, the NDA established a department for the implementation of geological disposal, which is planned to evolve into a 'delivery organisation' in the future. It is recognized that the NDA will need to reach out to relevant communities and stakeholders, including regulators, for the development of a coordinated strategy for the planning permission and regulatory approvals.

Based on the CoRWM recommendations of September 2008, a Joint Regulatory Office will be established (CoRWM 2009ba) to ensure more 'coherence and coordination' among the current regulators, the Health and Safety Executive (HSE) (Nuclear Installations Inspectorate, Office of Civil Nuclear Security and the UK Safeguards Office), the Environment Agency (EA), the Department for Transport (DfT) and the planning authorities. Legislative modifications are envisaged, for example changes to the provisions of the Radioactive Substances Act 1993 (RSA 93) to permit the authorization of GDFs in several stages, and changes to the Nuclear Installation Regulations 1971, such that disposal becomes a 'prescribed activity under the Nuclear Installations Act [1965]', thus enabling a GDF to be licensed 'as such' instead of purely as a storage facility (CoRWM 2009a).

The construction and operation of a GDF will be a long-term engineering project. The NDA's estimate of the undiscounted lifetime costs of a GDF is £12.2 billion (at 2008 prices), including research, design, construction, operation and closure (although this assumes that only one GDF will be required). The NDA's share of this amount is £10.1 billion, which is then discounted at 2.2% to give a discounted cost of £3.4 billion, the balance being payable by other users. Various factors will influence the actual cost, including the inventory of waste, the timing of waste production, the geology of the site in question and the design of the GDF (NDA 2009c).

4.3 Comparison of Geological Disposal of CO_2 and Radioactive Waste in the UK

A comparison of geological disposal of CO_2 and RW in the UK is provided in Table 11, which highlights both the similarities and the differences. The evaluation of the geological environment shows that offshore gas- and oilfields, as well as saline

Table 11 Comparative analysis of geological disposal of CO_2 and radioactive waste in the UK

Criteria	CO_2 disposal	Radioactive waste
Geological environment	Promising disposal options are offshore depleted oil- and gasfields; offshore and onshore saline aquifer formations. Unmineable coal seams are a less likely option because of their low permeability.	One third of the UK territory has geological environments that are in principle considered potentially suitable for the geological disposal of RW
Rock type and characteristics	Hydrocarbon fields Saline water-bearing reservoir rocks	Crystalline rock, indurated low-permeability sedimentary formations, plastic low-permeability sedimentary formations, evaporites——salt dome and bedded salt and some carbonates
Mode and purpose of disposal	The use of EGR and EOR for depleted oil- and gasfields is an advantage Injection of liquid supercritical CO_2 through wells for saline aquifers.	No specific disposal concept has been decided but the methodology employed in Sweden and Finland could be potentially applicable for emplacing HLW and spent fuel in tunnels
Volume (disposal capacity)	*Gasfields and condensate fields:* 5,982 Mt (75 fields); *Oilfields:* 4,225 Mt (74 fields); *Saline aquifers:* 14,446 Mt 32 sites)	HLW: 1,730 m^3 ILW: 92, 500 m^3 LLW: 196,000 m^3; the majority of LLW will not go to a GDF, but to a surface-based disposal facility; potential disposal capacity far exceeds waste volumes
Depth	Not above 800 m on account of the low density of CO_2	An engineered facility is likely to be located in the depth range of 300–1,000 m. If deep borehole disposal is used for some waste forms (HLW and spent fuel only) then depths as great as 5,000 m might be considered
Containment mode	Natural barriers with low permeability	Combination of natural barriers with engineered barrier systems
Site selection and public acceptance	Offshore oil- and gasfields, offshore and onshore saline aquifers identified as potential CO_2 disposal sites	No site has been selected
	To date there is no significant public opposition to CCD, but no specific sites have yet been proposed	Public consultation is in progress

(continued)

Table 11 (continued)

Criteria	CO_2 disposal	Radioactive waste
Implementation issues	*Regulation:* The regulatory arrangements are under development. New coal plants to be built in a design ready for later CCD fitting. The Energy Bill 2009–10 proposes financial support for four CCD demonstration plants. Office of CCS is to be set up to assist with the development and delivery of these.	*Legal and regulatory:* The legislation is in place, as the geological storage of RW is governed by the Nuclear Installation Act of 1965, but additional legislative changes have been recommended. A Joint Regulatory Office will also be set up by the current regulators (HSE, EA, DfT and the planning authorities) for greater coordination. NDA is the implementing organization, and the RWMD of the NDA is the delivery organization.
	Economics: CO_2 EOR may be economical in North Sea oilfields at an oil price of US $70–110 per barrel.	*Economics:* The NDA's current estimate of the undiscounted lifetime costs of a geological disposal facility is £12.2 billion (at 2008 values).
	Public acceptance: Favourable public support, although no specific sites mentioned; however, there is a need for long-term policy support in collaboration with international partners, as well as a reduction of the costs.	*Public acceptance:* Public consultation is in progress and both the UK Government and NDA are involved in public and stakeholder engagements but additional efforts are necessary to inform the public and local communities.

CCD carbon capture and disposal, *DfT* department for transport, *EA* environment agency, *EGR* enhanced gas recovery, *EOR* enhanced oil recovery, *GDF* geological disposal facility, *HLW* high-level waste, *HSE* health and safety executive, *ILW* intermediate-level waste, *LLW* low-level waste, *NDA* nuclear decommissioning authority, *RW* radioactive waste, *RWMD* radioactive waste management division

aquifers, are likely options for future CO_2 disposal. It is thought that approximately one third of the UK has geological environments which are, at least in principle, suitable for the geological disposal of RW. In the UK, hydrocarbon fields and saline water-bearing reservoir rocks are considered most suitable for CO_2 disposal. For RW disposal, a range of rock formations are considered as being potentially suitable. These include crystalline rocks, indurated low-permeability sedimentary formations, plastic low-permeability sedimentary formations, evaporates——salt dome and bedded salt——and some types of carbonates.

EOR or EGR provide potential advantages for CCD. Another option is using injection wells for saline aquifers, but the actual saline formations are not known and need further verification and testing to explore the viability of this option. In the case of RW, no decision has been made regarding the disposal concept. However, it is estimated that the disposal facility is likely to be located in the depth range of 300–1,000 m. If deep borehole disposal is used for some waste forms (this would be limited to HLW and SF), then depths as great as 5,000 m might be considered, while for CO_2 a depth of at least 800 m is required because of the low density of CO_2.

Major basins, offshore hydrocarbon fields and the major oil- and gas-bearing sedimentary basins have been identified for CO_2 disposal, including the southern North Sea Basin (gas), the central and northern North Sea basins (oil and gas) and the Irish Sea (gas). In the case of saline aquifers, the potential disposal sites are the southern North Sea gasfields. In the case of RW, no GDF site has been selected but there are several interim storage sites and more are planned.

The regulation of CO_2 disposal is still in progress, with some regulatory and legislative arrangements in place, for example: the UK Government announcement in April 2009 that all new coal plants are to be built with carbon capture ready technology; the Energy Bill, as part of the Draft Legislative Programme 2009/10, proposing financial support for four CCD demonstration plants; and the establishment of an Office of Carbon Capture and Storage to assist with the development and delivery of CCD. Compared with CCD, the regulations associated with the management and disposal of RW are mature. RSA 93 provides the legal framework for controlling the management of RW in a way that protects the public and the environment. It imposes requirements for registering the use of radioactive materials and for authorizing the accumulation or disposal of RW. Subject to the outcome of a UK Government review, RSA 93 may be replaced in England and Wales, possibly by 2010, by new regulations. New guidance on requirements for authorizing the geological disposal of RW was published in 2009 (EA and NIEA 2009), which supersedes the 1997 guidance, and allows for phased authorization, as the disposal programme proceeds. For more efficient regulatory mechanism a Joint Regulatory Office will be established among the current regulators, HSE, EA, DfT, and the planning authorities. On the implementation front, the NDA is the implementing organization, the RWMD is the delivery organization.

Some recent figures from the Scottish study (SCCS 2009) show that the cost for CO_2 EOR may be economical in North Sea oilfields at an oil price of US$70–110 per barrel, but no gross estimates are available for CO_2 disposal. Regarding RW, the NDA reported a figure of £12.2 billion (at 2008 prices) for the GDF, based on the undiscounted lifetime costs of a GDF, including costs related to research, design, construction, operation and closure.

With regard to the possibility of CCD, in general the public response has been favourable, as the technique is seen as a possible method for increased energy production without a concomitant increase in CO_2 emissions. The EU ACCSEPT survey results (Shackley et al. 2007) showed that British respondents were enthusiastic about the role of CCD in reducing carbon emissions. The UKCCSC survey cited some challenges to CCD, including the lack of long-term policy support, the cost and a requirement for an international regulatory framework. Public support for nuclear power has increased over the last few years. Consultations are currently in progress with interested communities on the possibility of locating a GDF, and both the UK Government and the NDA are involved in public outreach work. However, it is recognized that additional effort is necessary to inform the public and local authorities, especially those in the areas that have no previous experience of nuclear activities (CoRWM 2009a).

5 Summary and Conclusions

The broader socio-economic context and the many general energy and environmental regulations are similar in the three large EU countries analysed in this chapter. The EU-level energy and climate policies (particularly GHG and CO_2 mitigation targets) and the international conventions on RW management also provide a common framework for the national disposal strategies for CO_2 and RW. Moreover, the three countries cooperate in EU projects in both areas. Nonetheless, they seem to follow somewhat different strategies in their respective R&D and implementation.

Germany has considerable technical potential for both CO_2 and RW disposal. The optimistic estimate of the CO_2 disposal potential is in the range of 19–48 Gt CO_2, which is equivalent to 30–60 years of CO_2 emissions from all large stationary sources. The conservative estimate of 20 ± 8 Gt CO_2 is considerably lower. The total RW disposal capacity is assessed at more than 10 million m^3 (about 200 Mt), which could accommodate RW for hundreds of years of expanded nuclear power generation, even without any waste minimization strategy.

While the legal basis for RW disposal has been in place for 50 years, that for CO_2 disposal has emerged only recently. The German CCD act was passed in early 2009, and the BGR is developing standards and criteria for CO_2 disposal sites. Geological disposal of RW is governed by the German Atomic Energy Act of 1959, the revisions thereof, and the Mining Law, and is the exclusive responsibility of the government. As a result, an interesting dichotomy can be observed in the management process in Germany. The site selection for CO_2 disposal is carried out by researchers and the private sector with very little government involvement; site selection for RW disposal is entirely a government-driven process.

So far there has not been much public discussion about the benefits and drawbacks of CCD owing to limited knowledge about this technology. Experts and industry representatives tend to be optimistic about CCD, whereas environmental organizations have declared serious reservations or outright opposition. As far as RW disposal is concerned, site selection criteria have been officially adopted and have barely changed over the past 40 years, but public discussion and socio-political issues have become increasingly important. The political debate culminated in the decision by the Federal Government in 2000 to suspend all exploration at the Gorleben site, which had been selected in a long and thorough assessment process about 20 years before. A government task force in 2002 suggested that a completely new site selection process be started. While the Gorleben moratorium remained in place through mid-2010, no significant effort has been made to start a new site selection process.

In France, CO_2 disposal capacities in the Paris Basin have been partially estimated for two targeted types of geological formations that host aquifer and hydrocarbon fields. Other basins may have a bigger capacity, but given the proximity to the major emission sources, which is one of the key issues in the search for the disposal site, the Paris Basin has been studied the most extensively. The capacities in the Paris Basin have been estimated to lie within the range of 0.3–29.1 Gt CO_2 for the aquifer and 83–117 Mt for hydrocarbon fields. In comparison to France's annual emissions of 390 Mt of CO_2 for 2005, the estimated capacity is viewed as limited in this region.

RW that will have been produced by 2055, including that already produced and stored for final disposal, is estimated to have a volume of 7,912 m^3. The overall capacity of potentially suitable sites in France is much larger than this and a single site, such as the one currently being investigated for its suitability at Meuse/Haute Marne, is expected to host all the existing and foreseen HLW and SF. This is in contrast to the situation for CCD, which would likely require multiple sites for disposing of the greater part of the CO_2 expected to be generated in France over the foreseeable future.

Implementation efforts in the area of RW disposal in the 1990s faced difficulties, as the lack of a public consultation procedure led to strong local opposition against underground research laboratories, which halted the site selection process for a year. Learning from this experience, research on the disposal of HLW has since been strongly regulated by laws, and steps and procedures for public consultations have now been established. For the geological disposal of CO_2, there is at present no comprehensive regulatory framework. Therefore experience from the RW management process might provide useful lessons for the management of CO_2 disposal.

Compared to some other EU countries, the UK has proposed tougher targets to mitigate climate change. It aims to reduce GHG emissions by 20% from 1990 to 2020 and by 80% from 1990 to 2050. With respect to CO_2, legally binding targets have been set in the Climate Change Act of 2008 that require UK CO_2 emissions to be reduced by 26% from 1990 to 2020.

The most significant option for the disposal of CO_2 is offshore sedimentary basins that contain most of the UK's oil- and gasfields. About one-third of the UK might be appropriate for geological disposal of RW due to the availability of suitable and stable rock formations for hosting a geological disposal facility.

The UK Government has taken firm measures to implement and develop CCD technologies and has proposed financial support for four CCD demonstration plants. It has also initiated steps towards the implementation of a geological RW disposal facility and has tasked the Nuclear Decommissioning Authority with managing HLW.

Considerable R&D and implementation-related activities to foster the geological disposal of CO_2 and RW are underway in many other West European countries. In-depth comparative assessments in the national context may well lead to interesting insights, similar to those emerging from the analyses presented in the preceding sections of this chapter.

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