Carbon Dioxide and Radioactive Waste in Central and Eastern Europe: A Regional Overview of Geological Storage and Disposal Potential

Zsuzsanna Hódossyné Hauszmann, Péter Scholtz, and György Falus

Abstract Given that carbon dioxide (CO_2) capture and storage is a promising option for reducing greenhouse gas emission levels and that nuclear power-based energy production is a proven carbon-free technology, we give a regional overview of the geological storage potential of CO_2 and disposal potential of radioactive waste in eight countries of Central and Eastern Europe (CEE): Bulgaria, Croatia, the Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia (referred to here as the CEE-8). A region-specific summary of CO_2 emission point sources and emission figures is given as well as of nuclear power plant facilities, their waste types and respective volumes. In addition, we provide a description of the geological storage types available for CO_2 in the CEE-8, namely depleted hydrocarbon fields, saline aquifers and coal reserves. We give insights into the determining factors for site selection for geological storage of CO_2. We review the countries in the region that are considering and/or working on a radioactive waste disposal facility. An assessment is provided on the status of the site selection programme, if any, in each country. Potential geological features are summarized in terms of possible disposal sites. We compare the identifiable similarities and differences in geological storage of CO_2 and disposal of radioactive waste among the countries studied and between the two types of substances to be disposed of.

Keywords CO_2 • Radioactive waste • Central and Eastern Europe • Geological storage • Radioactive waste disposal

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1 Introduction

In view of rising global energy demand and the absence of a breakthrough in carbon-free technology, a portfolio of options is needed to manage the risks of global climate change, with as many sustainable options as possible being used and developed. Carbon capture and storage (CCS), that is, the capture of carbon dioxide (CO_2) produced from chemical and combustion processes and its storage in geological formations, is a relatively new option that is rapidly gaining support. In a study released in December 2004, the OECD International Energy Agency (IEA) states: 'CCS is a promising emission reduction option with potentially important environmental, economic and energy supply security benefits.' (IEA 2004) On a lifecycle basis, nuclear power is a low-carbon technology and has the potential to supply a substantial part of the world's electricity needs. Unfortunately, the high initial capital needed to build a nuclear power plant (NPP), along with environmental and security issues, limit the capacity of countries to establish or extend their reliance on nuclear energy. A major obstacle in this process is the safe disposal of radioactive waste (RW), for which geological disposal is an established and accepted solution.

The official announcement by the European Union (EU) of Europe's commitment to reduce greenhouse gas emissions by 20% by 2020 has put clear pressure on governments and industry in Europe to seriously address emission reduction options. This is particularly so in the case of the countries involved in this study: Bulgaria, Croatia, the Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia (referred to collectively here as the eight Central and Eastern European countries, or CEE-8). The threats, damage and the overall negative effect of climate change are starting to be understood by a wide cross section of the general public, and also by research and industry in the CEE-8. Most stakeholders in the region now readily agree that action must be taken. However, there is no consensus among the stakeholders as to what form this action should take; this, though, is probably due to a lack of knowledge regarding possible climate change mitigation options.

2 CO_2 Emissions and Radioactive Waste Generation

The structure of energy production is similar in each of the target countries, being largely based on fossil fuel combustion, in many cases with very low efficiency (for instance, a lignite power plant has only 30% conversion efficiency). The role of natural gas in energy production has risen in the last few decades and is expected to increase continuously in the short to long term.

According to the national greenhouse gas inventories of the CEE-8 for 2005, CO_2 emissions from point sources account for a total of approximately 510 million tonnes (Mt)/year. These point source emissions are responsible for more than 70% of the total emissions of the CEE-8 countries.

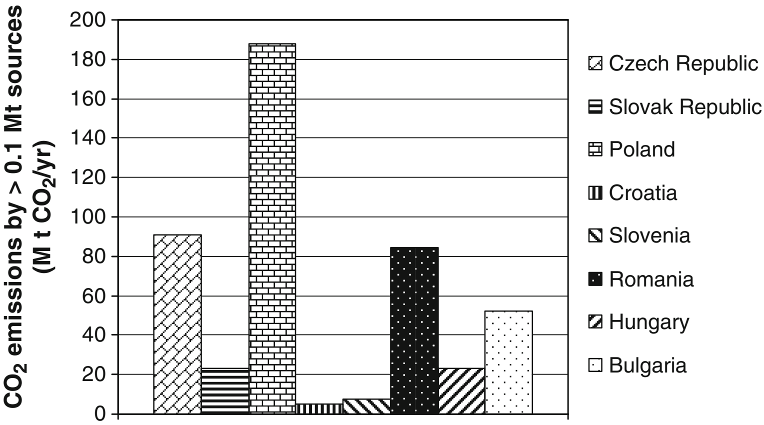

Fig. 1 Annual CO_2 emissions by larger point sources in the CEE-8 countries

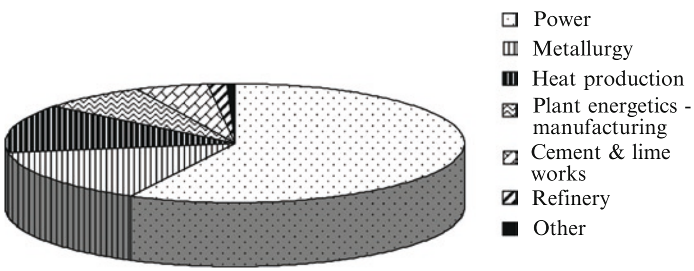

Fig. 2 Relative distribution of CO_2 emissions among industries in the Czech Republic

To obtain information about the geographical distribution of CO_2 emissions, an inventory of point sources greater than 100,000 t CO_2/year was created. The inventory output is presented in Fig. 1.

Power plants have the highest emission rates, followed by heating facilities and energy producers for manufacturing industry. The typical distribution of emissions across different industry segments in the Czech Republic is shown in Fig. 2. Metallurgical plants are also major emitters, particularly in Slovakia; cement and lime works and chemical factories are among other major contributors.

The CO_2 concentration in industrial exhaust gases is usually lower than 20% on account of the combustion processes used. The exception is chemical factories, where CO_2 concentration in the flue gas is much higher.

The generally accepted pathway to decreasing CO_2 emissions in line with EU reduction prescriptions is to increase energy production and consumption efficiency. Nevertheless, CCS is also beginning to be accepted as a viable way of mitigating the effects of climate change. While the research and industrial sectors in the

CEE-8 are preparing to start deployment of CCS in the near future, governments are lagging behind. Nevertheless, the regulations, financing strategy and overall understanding of the role of CCS in climate change mitigation and its context in energy and energy safety are improving at the political level.

Nuclear energy accounts for 16% of global electricity production. NPP operations produce most of the RW, making appropriate nuclear waste management and safe disposal indispensable. However, waste is also derived from the use of radioactive substances for medical, agricultural, research-related, industrial and educational purposes. RW can also originate from certain specific sources such as, for example, naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM). As the overall radiotoxicity of the waste from these sources is low, we deal here only with RW from the nuclear industry.

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

The requirements for a deep geological repository are not just technical (although these are perhaps the main issue), but go above and beyond a straightforward technical feasibility study and a demonstration of safety to meet regulatory standards. They also include ethics, security, environmental acceptability, public acceptance and economic viability.

In the CEE-8 there are 22 nuclear power units at eight locations, as shown in Fig. 3. Two countries, Croatia and Poland, have no NPPs. Most of Poland's energy requirement is met by coal-based power plants. The rest comes from wind and hydroelectric plants. Krško NPP in Slovenia meets some of Croatia's energy requirements.

All CEE-8 countries, apart from Croatia and Poland, have RW disposal facilities (see Fig. 3). The existing facilities allow disposal of short-lived low- and intermediate-level waste (LILW-SL) and, in certain cases, long-lived low- and intermediate-level waste (LILW-LL). The repositories used are surface repositories, except in Romania, which has a geological facility. The current host rocks for these repositories are clay loess, sandy clay, granite, sedimentary and crystalline rocks.

In every CEE-8 country that has RW disposal facilities, the volume of high-level waste (HLW) is very low compared to other types of RW. The HLW produced through the operation of NPPs is usually represented by the spent fuel kept in interim storage facilities at these sites. The statistics that follow below regarding spent fuel and HLW on a country-by-country basis are taken from the International Atomic Energy Agency (IAEA 1997).

In Romania the total amount of fuel that will have accumulated by 2020 is estimated to be 4,170 t of heavy metal (tHM). In the Czech Republic HLW from decommissioning is estimated at about 20,000 m^3 and the volume of spent fuel at around 3,000 tHM. Bulgaria has sent some 1,168 spent fuel assemblies to Russia, which will all eventually be returned as vitrified HLW. This amount could rise to 7,331 in the future, effectively covering all the spent fuel currently in storage at NPPs, namely around 100 m^3 of vitrified HLW. In Hungary there could be 200 m^3

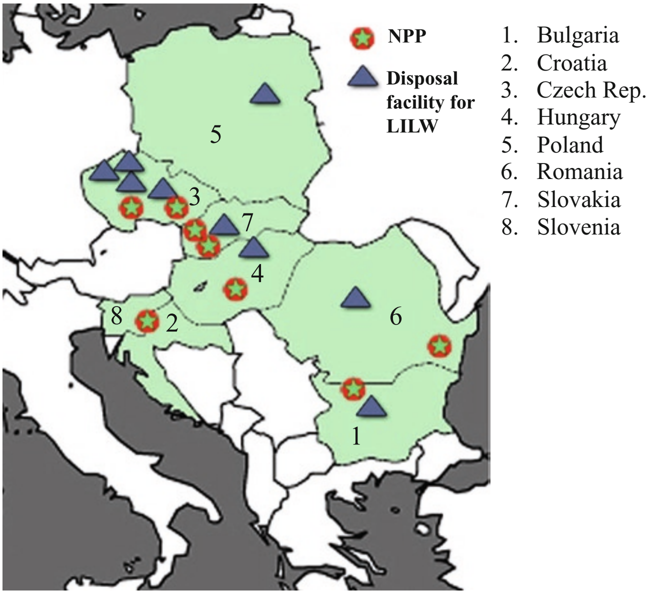

Fig. 3 Location of existing disposal facilities and nuclear power plants in the Central and Eastern European region (*see* Colour Plates)

of HLW resulting from NPP operation by 2032. The average amount of HLW generated is 5 m^3/year, and storage capacity at the Hungarian site is 220 m^3. Spent nuclear fuel (SNF) is kept in an interim spent fuel storage facility. The projected total number of SNF assemblies is 11,000 (1,286 tHM) in 2017. In Slovenia the total storage capacity of the spent fuel pools is 1,694 fuel positions. The decommissioning programme will result in a total of 620 tHM spent fuel assemblies and 16 m^3 of HLW. In Slovakia the total inventory of SNF in 2039 (after the decommissioning of all six nuclear power units) is estimated at 2,374 tHM (18,654 fuel assemblies). Slovakia also has another 2,600 m^3 of long-lived RW.

3 Current Status and Issues of Geological Storage of CO_2 in the Region

The main aims of geological storage of CO_2 are to prevent a large amount of anthropogenic CO_2 being emitted to the environment and to keep it isolated from the atmosphere in secure long-term storage. There is a strong tendency in Europe to standardize site selection criteria in order to reduce storage-related risks. The partners in the EU GeoCapacity project under the Sixth Framework Programme are assessing storage potential and have developed and adopted a series of criteria for use in their site selection procedures to ensure quality and consistency (see, e.g. Saftic et al. 2007, 2008; Hatziyannis et al. 2007, 2008; Sliaupa et al. 2007; Wojcicki 2008; Tarkowski et al. 2008; Martinez et al. 2008; Georgiev 2008; Kuharic 2008). The criteria are intended to serve as the basis for a standardized procedure in future site selection processes (see EC 2009), and focus primarily on the adequate storage potential and appropriate seal integrity of the potential storage complexes (storage formation and surrounding geological environment).

3.1 Main Selection Criteria Concepts

One of the main selection criteria (see Table 1) is that the reservoir should be deep enough to store CO_2 safely, as this ensures that CO_2 stays in its dense phase, which results in low positive buoyancy and makes storage more economically viable. As the storage depth is usually compromised with decreasing porosity and permeability, storage depth is recommended to be not greater than 2,500 m unless there are authoritative data to validate acceptable porosity and permeability values at greater depth (Chadwick et al. 2007).

Seal integrity is considered the most important criterion for site selection. In the geological storage of CO_2, only the geological barrier itself prevents CO_2 from escaping to the environment. The presence of an adequate seal, capable of restraining CO_2 in the reservoir at a given pressure, temperature and chemical composition, is thus essential. Seals are low permeability rocks, typically shales and mudstones with a minimum thickness of 20 m.

Any reservoir used for CO_2 storage should also possess effective petrophysical reservoir properties. Satisfactory reservoir properties (i.e. high permeability and high porosity) are essential to ensure sufficiently high injectivity to make the process economically viable and to guarantee sufficient storage volume.

As investment costs are expected to be the most important among the non-geology-related limiting factors in CO_2 storage, an important aspect of the ideal storage site is sufficient storage volume. The site selected must be capable of storing CO_2 released from the emission source.

3.2 Storage Types

Natural examples and a number of ongoing projects clearly demonstrate that CO_2 can be safely stored in appropriate geological formations such as depleted oil and gas reservoirs, deep saline aquifers and unmineable coal reserves (Fig. 4). Globally, geological formations represent a large storage capacity. Although there are wide differences in storage capacity depending on local geology, it can nevertheless be concluded that the capacity is sufficient to store worldwide anthropogenic CO_2 emissions for decades, and possibly centuries.

Table 1 Key geological indicators for CO_2 storage site suitability (Based on Chadwick et al. 2007)

Basic geology-related criteria	Influential geological and physical parameters	Criteria to be investigated in the screening process	
		Positive indicators	Cautionary indicators
Sufficient depth of reservoir	Pressure Temperature	Depth of crest of reservoir >1,000 m	Depth of crest of reservoir <800 m
		Depth of base of reservoir <2,500 m	Depth of base of reservoir >2,500 m
Petrophysical reservoir properties	Porosity	>20%	<10%
	Permeability	>300 mD	<200 mD
Integrity of seal	Lithology	Low permeable lithologies such as clay	
	Porosity		
	Permeability		
	Thickness	>100 m	<20 m
	Faults	Unfaulted	Faulted
	Heterogeneity	Homogenous	Heterogeneous
	Tectonic activity	No tectonic activity	Tectonic activity
Storage capacity	Reservoir	Total capacity of reservoir estimated to be much larger than the total amount produced from the CO_2 source	Total capacity of reservoir estimated to be similar to or less than the total amount produced from the CO_2 source
	Thickness	>50 m	<20 m
	Area	Well defined	Not well defined
	Heterogeneity		
	Faults	Unfaulted	Faulted
	Trap type	Well defined structures	Not well defined
	Petrophysical properties	Values given above	Values given above

mD millidarcy

3.2.1 Hydrocarbon Fields

Hydrocarbon fields could be the first geological sites to be used for CO_2 storage in many of the CEE-8 countries. This is because:

1. Their geological, structural and dynamic characteristics are well known and have been studied for a long time, in some cases for several decades;
2. It is possible to combine CO_2 storage with enhanced oil (and gas) recovery, which could offset the costs of CCS. Croatia, Hungary and Romania now have significant experience in enhanced oil recovery techniques, especially using CO_2, dating back to the early 1970s;
3. The regulatory framework in the CEE-8 (and overall in Europe) permits CO_2 storage in hydrocarbon reservoirs.

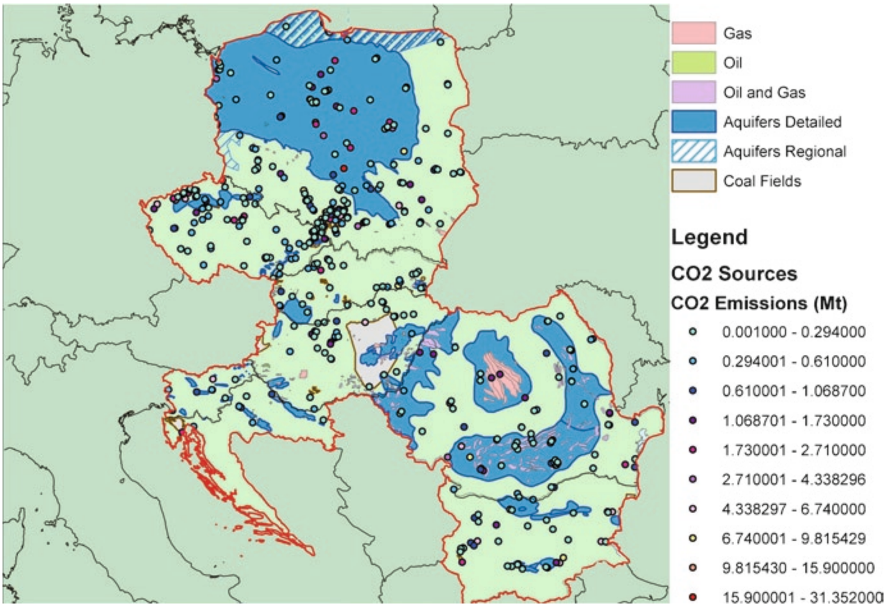

Fig. 4 The study area with larger emission point sources (*circles*), depleted hydrocarbon fields, saline aquifer and unmineable coal reserve sites (*see* Colour Plates)

Existing and depleted fields are mainly onshore, but Bulgaria, Croatia, Poland and Romania also have some offshore production. Hydrocarbon fields and associated storage capacities, although unevenly distributed, are concentrated in the Pannonian Basin and the Carpathian foredeep basins in the CEE-8 countries (see Fig. 4). The overall potential storage capacity is over 2,000 Mt; however, some fields will not be available for many years and this, together with strong competition between CO_2 and natural gas for storage, implies that there will not be much volume available for CO_2.

3.2.2 Unmineable Coal Reserves

There is far less geological and engineering information available on unmineable coal seams than on hydrocarbon fields. Nevertheless, there is a reasonable amount of knowledge about their geological and structural characteristics and their physical properties, especially in Poland where coal is the main source of energy production.

The methodology of CO_2 storage in unmineable coal seams is far less developed than that of storage in depleted hydrocarbon reservoirs. There are obstacles (i.e. low permeability, heterogeneity, timeliness of adsorption–desorption mechanisms) which need to be dealt with before unmineable coal seam storage can be used commercially.

Nonetheless, there are two important aspects related to CO_2 storage in coal seams in the CEE-8: (1) large coal-based power plants are usually very close to the potential coal storage sites; and (2) CO_2 storage could be linked with methane exploitation, which would compensate for CCS costs.

According to studies carried out in the course of the EU GeoCapacity project, the highest potential for storage with associated methane production is in the Czech Republic, Hungary and Poland (Fig. 4). There is less potential in Bulgaria, Romania and Slovenia, and in Croatia and Slovakia the potential is negligible. The overall storage capacity in the Czech Republic, Hungary and Poland is around 700 Mt associated with the production of about 180 billion m^3 of methane.

3.2.3 Saline Aquifers

The most promising areas for CO_2 storage are thought to be saline aquifers, which are present in all the CEE-8 countries and have a potentially much higher storage capacity than hydrocarbon fields and unmineable coal seams. Ideal aquifers have vertically closed structures with adequate sealing and significant pore volume capacity. Although saline aquifers have the greatest potential storage capacity, a lack of economic interest in this kind of storage option in the past means that available public data are not detailed enough for an accurate estimate and comprehensive characterization. The quality and the availability of data for reliable calculations vary from country to country. The potential storage areas in the CEE-8 region are shown in blue in Fig. 4. Details are as follows:

- In Poland, the approximate locations of 19 structures ranging from 100 to 625 km^2 were determined based on Mesozoic Formation maps by Dadlez (1998).
- In Croatia, five regional aquifers were identified, four of which lie in the Pannonian Basin and one offshore in the Adriatic Sea.
- Calculations are to be carried out regarding the storage capacity of two large basins in Slovakia: the Eastern Slovakian Basin and the Danube Basin. The most important strata with known aquifers are the Sarmatian, Pannonian and Pontian sediments.
- Altogether, 22 potentially suitable structures were identified in the Czech Republic, 17 of them in the Carpathians (the eastern part of the country) and five in sedimentary basins of the Bohemian Massif.
- In Slovenia, 35 potential locations were identified for CO_2 storage in aquifers.
- The first estimation of CO_2 storage potential for Bulgaria based on well logs and seismic investigations shows that there are several potential aquifers, related to Devonian, Lower Triassic, Middle Jurassic, Valanginian and Eocene reservoirs.
- In Romania, four large basins filled with clastic sediments represent enormous potential for CO_2 storage. Storage formations with potentially adequate capacity are mostly young Miocene–Pliocene clastic basin fills.
- There are six large regions in Hungary associated with basement highs and structural and lithological closures that are potential aquifer storage sites. Like the Romanian, Slovakian and Croatian examples, these aquifers are mainly related to young Miocene–Pliocene sediments.

The overall potential storage capacity in the CEE-8 is very high, representing several tens of gigatonnes. However, the capacities mentioned should be treated as first rough estimates of real storage capacity. Further research concerning porosity, permeability and structural closure parameters are essential if aquifer storage is to become realistic. It is expected that the actual storage potential will be considerably lower than stated here.

4 Current Status and Issues of Geological Disposal of Radioactive Waste in the Region

A rock formation is the most likely solution for HLW disposal. Geological disposal is the disposal of solid RW in a facility located underground in a stable geological formation (usually several hundred metres or more below the surface) that provides long-term isolation from the biosphere of the radionuclides in the waste. Based on a Safety Guide published by the IAEA (1994), we summarize here the different factors to be taken into account in the countries' site selection programmes.

The geological environment is expected to contribute towards ensuring safe disposal in three ways, namely by:

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

Siting of such a storage facility is a multistage process. Several factors need to be considered when a site is being selected. These are:

- Geological setting;
- Possible future natural changes;
- Hydrogeology;
- Geochemistry;
- Events resulting from human activities;
- Construction and engineering conditions;
- Transportation of waste;
- Protection of the environment;
- Land use;
- Social impacts.

Several CEE-8 countries have screened their territories for suitable geological sites and are considering construction of a geological HLW disposal facility (see Fig. 5). Certain selection criteria have been determined, leading to a more detailed

Fig. 5 Location of candidate areas for deep radioactive waste geological repositories in the Central and Eastern European region

analysis of prospective areas and the choice of a site. The countries' site selection programmes consist of four different stages:

1. Conceptual and planning;
2. Area survey;
3. Site characterization;
4. Site confirmation.

The works of Witherspoon and Bodvarsson (2001, 2006), Witherspoon (1991, 1996), Chapman (2006) and the OECD Nuclear Energy Agency (NEA 2004) have been used in research relating to deep geological repositories.

4.1 Bulgaria

The Bulgarian Government approved a national strategy for safe management of SNF and RW in 1999. This strategy includes deep geological disposal of HLW and near-surface disposal of conditioned LILW. After the preliminary screening of the national territory, 30 sites were selected using exclusionary criteria (28 mainly geological criteria), from which four sites were chosen. Two sites are composed of Lower Cretaceous clayey marls in north-west Bulgaria and two sites are in Sakar granite pluton in the south-east of the country.

The potential sites in the Lower Cretaceous marls are about 50–55 km south of the Kozloduy NPP (see Fig. 5). These two sites have similar conditions: they are about 750 m thick at one site and 1,000 m thick at the other; the formations consist mainly of clayey marls and rare thin-layered sandstones. The composition of the marls guarantees good sorption properties. The unconfined compressive strength values vary between 11 and 29 MPa. The Lower Cretaceous marls are known to be water-impervious layers. The sites are located in a region with a seismic intensity of VII on the MSK-64 scale. Seismicity has no connection with the fault structures of the area. Both marl sites are suitable not only for a deep HLW disposal but also for a near-surface LILW repository. This means that both types of repository could be constructed at the same site.

Two sites in the Paleozoic medium-grained granites of the Sakar pluton have been studied in detail, and these can also be discussed jointly. Both sites are situated about 300 km from the Kozloduy NPP. Their mineral composition is mainly plagioclase, orthoclase and quartz. The bulk density of granite is 2.62 g/cm^3, the density of solid particles 2.7 g/cm^3, the absorbed water content 0.35% and the unconfined compressive strength about 120–140 MPa. Analysis of the topographic and tectonic features of the sites suggests that the isolation capability of the deep disposal system will not be disturbed by erosion processes in the next million years. The sites are located in a region with a seismic intensity of VIII on the MSK-64 scale. The investigations indicate that the granite host rock at both sites is a suitable host medium for deep RW disposal.

In the early 2000s, analysis and explorations were carried out in a 25–30 km zone around the Kozloduy NPP to evaluate the geological conditions for RW disposal. The available data show that sediments with small discontinuities are represented in the geological profile. These sediments include the Middle and Upper Paleogene and Neogene formations. The Paleogene sediments consist of three formations: lower, marl–sandstone–limestone; middle, marl; and upper, silty clay. The middle and upper formations could be considered potential host media for geological disposal. They have a total thickness of 300–400 m. The Neogene, exceeding a depth of 1,000 m in the region of the NPP, is represented by sediments of the Miocene and the Pliocene.

Table 2 summarizes the features of the Neogene formations.

From the seismic point of view, the Kozloduy region appears to be one of the most geologically calm areas of Bulgaria. To summarize the recent research results, the main conclusion is that there is a possibility of developing a site in the vicinity of the Kozloduy NPP for deep HLW disposal and also for a near-surface LILW repository. Any decision will be based on further investigations and other important considerations (e.g. safety, waste transport, infrastructure, support of the local population, etc.).

4.2 Poland

Poland has no NPPs, but the country has its own nuclear power programme. A strategic government programme entitled Radioactive Waste and Spent Nuclear Fuel Management in Poland was conducted from 1997 to 1999. The aim of the

Table 2 The potential sites of a deep geological repository in Neogene formations in Bulgaria

Formations	Composition	Thickness (m)	Age
Miocene			
Delein	Greyish-blue clays with clayey limestones, silty clays and sandstones	200–440	Badenian
Krivodol	Grey and greyish-blue clay, stratified silty and calcareous clay with marls, dense clayey limestones and sandstones	120–240	Sarmatian
Pliocene			
Smirnenski	Grey and grayish-green low-calcareous, silty clays with clayey limestone and marl	200–250	Meotian–Lower Pontian
Archar	Sand	80–100	Upper Pontian
Brusarci	Clays with sand intercalations	50–200	Dacian–Romanian

programme was to investigate the legislative, institutional and technical issues relevant to RW and SNF, as well as public information issues, which were an essential element of the programme. Likewise, under this programme, a feasibility study of future repositories for SNF and HLW, as well as a study of all unmined deposits and rock formations in the existing deep excavations were performed. The study eliminated from consideration all deep mines currently under exploitation because of potential water threats, static distortion of formations or fissures caused by mining activities, the vicinity of current underground works and the seismicity of the area.

After a review of the geology of Poland, 44 rock formations were selected for further investigation. These included 17 sites in igneous (mainly granitic) and metamorphic rocks, 7 sites in shale and 20 sites in salt deposits. During the second stage of evaluation of potential sites, four geological structures were chosen as promising. These are Triassic clay rocks in south-west Poland and three salt domes in central Poland. The candidate sites were selected on the basis of preliminary geophysical investigations and the study of archive geological and hydrogeological data.

The general criteria for RW disposal in shale are:

- Shale beds to be at least 200 m thick;
- Overlying rocks to be at least 300 m thick.

Based on the general criteria with respect to shale, the candidate site was selected in the Triassic shale (near Jarocin), also known as the Upper Gypsum Beds.

The following initial criteria were considered for RW disposal in salt domes:

- Rock salt to occur at a maximum depth of 600 m below the ground surface;
- Overlying rocks to have a minimum thickness of 400 m;
- Homogeneous rock salt to have a minimum thickness of 250 m;
- Disposal zone thickness to range between 20 and 200 m;
- Maximum depth of repository to be <1,200 m below the ground surface.

Regarding disposal in salt domes, there are three candidate sites: Damaslawek, Klodawa and Lanieta. Lanieta has been explored in very great detail because of its economic importance for salt mining. In Damaslawek, two potential waste repository sites have been suggested in the central part of the salt dome, based on geophysical data. In the Klodawa salt dome, a future repository can be located some 2 km away from tunnels in the Klodawa salt mine.

4.3 Hungary

Because of the country's geology there are only a limited number of potentially suitable disposal sites for HLW in Hungary, which is why selection was carried out without preliminary national screening. The research regarding a suitable geological host site began with the Boda Claystone Formation (BCF) near the city of Pécs in south-western Hungary. Close to part of the BCF is a Permian sandstone formation. Information about the lithology, structure of the overlying sandstone and groundwater flow conditions of the sandstone was collected during operations at the Mecsek uranium mine (now closed) over the past 40 years. A specific study programme was started in 1993 to conduct a further examination of the BCF.

In 1994 the exploration tunnel excavated in the Mecsek uranium mine reached the claystone formation, and on-site underground data acquisition began in this area at a depth of 1,000 m (accessible from the former uranium mine). The possibility of implementing in situ examinations at this depth is very rare. Between 1995 and 1998, a short-term programme was launched to characterize the rock mass. The results are summarized below.

The recent 700–1,000 m thick layers of the BCF were settled in an alkaline basin under extreme climatic inflow and geochemical conditions and later buried at a depth of at least 3.5–4.5 km. The bulk porosity and hydraulic conductivity of the intact rock matrix are 0.6–1.4% and 10–15 m/s. The typical interval for the Young modulus is between 30 and 40 GPa, and the average unconfirmed strength exceeds 100 MPa. The dominant clay mineral in unweathered rock types of the BCF is illite (25–40%).

In 2000 the uranium mine was closed after plans for an underground research laboratory at the BCF site were rejected by the Government. A new policy initiative was launched, with the Public Agency for Radioactive Waste Management (PURAM) contracting the Empresa Nacional de Residuos Radiactivos (ENRESA) of Spain as a consultant organization to develop a strategy for disposal of high-level and/or long-lived radionuclide waste and SNF management. The long-term strategy is based on the ENRESA study. To ensure the safe disposal of HLW, the construction of a repository in a deep geological formation within Hungary is vital. Such a repository could also be used for direct disposal of SNF and, even more importantly, for the disposal of waste from the reprocessing of SNF assemblies.

Also in 2000, nationwide screening was carried out using desk studies to evaluate the potential rock formations in detail. This investigation confirmed the primacy of the BSF among the potentially suitable sites for an HLW repository. In 2004, in parallel with policy development, an exploration programme for an HLW repository restarted at Boda. The investigation had to be carried out from the surface because the uranium mine was no longer accessible. The aim was to pinpoint a location for an underground research laboratory (URL) from which rock investigation could be conducted.

The time schedule for the disposal of HLW and the management of SNF is presented below:

Time period	Tasks
2005–2008	Start of R&D work • Surface exploration of the BCF region for the construction of a URL • Preparation of a Preliminary Environmental Impact Study Report • Finalization and approval of the HLW management strategy
2009–2012	• Start of construction of the URL • Elaboration of a research/exploration programme
2013–2032	• Construction of the URL • Implementation of research/exploration • Completion of safety assessments
2033–2046	• Construction of the repository
2047–2069	• First phase operation of the HLW repository • Transfer of spent fuel assemblies from the Interim Spent Fuel Storage Facility to the repository
2070–2094	• Operation of the repository
2093–2094	• Extension of the capacity of the repository to accommodate the decommissioned HLW
2095–2104	• Second phase operation of the HLW repository • Transfer and loading of the decommissioned waste (HLW) from Paks NPP
2105–2108	• Sealing of the repository

4.4 Slovenia

In Slovenia a strategy on SNF and HLW was adopted by the Government in 1996, but it was recommended that any decisions on SNF disposal should be postponed until 2020 and that no significant action should be taken until then.

In 2004 the disposal strategy was reinvestigated, after the dual ownership of the Krško NPP had finally been clarified and agreed upon between Croatia and Slovenia. According to the agreement, the decommissioning and disposal of SNF and LILW from the NPP is the responsibility of both parties. To address this problem, a joint programme was instituted by the Croatian and Slovenian waste management organizations in 2004. The preliminary aim of the joint programme was to provide an accurate estimate of the future liabilities of the NPP.

As there are small quantities of HLW and SNF and limited financial resources at Krško NPP, a very rational approach was required. An example of the best practice available was followed: this was the Swedish KBS-3 concept of disposal in hard rock, and its cost analysis method. Many adjustments were required before this approach fitted the needs of Krško, and some additional control measures were also introduced.

In developing the disposal concept, the following additional assumptions were taken into account:

- Only direct disposal of SNF would be considered (no reprocessing).
- The repository would be developed for a hard rock environment at a depth of 500 m.
- The capacity of the repository would be such as to accommodate the estimated 620 tHM that would be generated over the plant's lifetime and the small quantities of HLW generated during decommissioning.

Regarding the timing, two alternatives were analysed:

1. The repository would be available and would start operation shortly after the plant shutdown in 2030. As SNF could be stored in the SNF pool on the NPP premises, no interim storage of SNF would be needed.
2. The repository would become available a few decades after the plant shutdown and would enter into operation in 2050. Until then, a longer interim dry storage period for SNF would be applied before final disposal.

A reference scenario was developed that:

- Covered only SNF and HLW management at the Krško NPP, which would cease operating in 2023;
- Assumed that all SNF would be disposed of in a single deep geological repository;
- Covered a generic location in hard rock media, given that no site investigations for a deep geological repository have been carried out in Slovenia and that no specific data for geological disposal are available;
- Was limited to those elements that were directly connected to disposal activities (packaging and disposal of SNF);
- Included an encapsulation plant for SNF at the site, as SNF would be sealed in a massive copper canister.

A comparison between the two alternatives for repository development reveals strong technological and economic preferences for the second one. In this alternative, the plan is for operation of the repository to begin almost 30 years after plant shutdown, allowing sufficient time for the site selection process. Heat release from SNF is low enough for the canisters to be filled optimally, thus almost halving the number required and consequently shortening the operation of the encapsulation plant and repository.

The agreement requires revision and updating of the joint decommissioning and the SNF and LILW disposal programme every 3–5 years. Revisions will focus on possible optimizations of the disposal system.

As the disposal activities are planned for the fairly distant future, there is time for other possibilities to be investigated. Disposal concepts in other geological environments will also be studied. Multinational shared repositories are another option that may be interesting for Slovenia with its small quantities of SNF and HLW.

4.5 Croatia

For Croatia, only information concerning LILW disposal is available (see also the details on Slovenia).

4.6 Czech Republic

The Czech programme for a deep geological repository began in 1993 with the project 'A selection of prospective HLW disposal sites in the Bohemian Massif'.

During the first stage of the site selection programme, 27 areas were identified from the geological, hydrogeological and geophysical viewpoints. Most of the national territory is crystalline rocks (more than 60%). These rocks exhibit favourable characteristics for hosting an HLW repository. These 27 localities were reviewed and the 13 most suitable sites were recommended for critical assessment based on archive data. The area of the recommended sites ranges from 20 to 120 km^2. As a result of this assessment, eight localities, all in granitic rocks, were recommended for further detailed geological survey. The Melechov Massif in the Central Moldanubium Pluton was chosen as a test site and for the first stage of research (an evaluation and study of its geological, hydrogeological, geophysical, tectonic and structural properties have already been completed). This test site represents an area that is analogous with the host geological environment for future HLW and spent fuel disposal in the Czech Republic. It is important to note that the deep repository will not be built at this site, although it is suitable for research targeting the sampling and collection of descriptive data using the most advanced scientific methods.

Next, four polygons were selected to represent all types of the Melechov Massif on which detailed geological, geophysical, hydrogeological, structural, geochemical etc., research were carried out. This work covered all non-destructive geoscience methods and prepared suitable data for the siting of boreholes for conducting:

- Well logging measurements;
- Geophysical, hydrogeological tests;
- Physical property estimation of different rock types;

- Petrographical and petrochemical study of samples;
- Mathematical modelling of fluid migration and micro and macro structures.

In 1997 the RW management system changed significantly, when a new law on the peaceful utilization of nuclear energy and ionizing radiation was passed. A key document, The Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic, was published in 2001. The Concept sets out the basic aims and direction for the development of the RW and SNF management system.

A number of studies aimed at locating a site for a future deep geological repository were carried out. Their main objective was to collect and evaluate existing geological information relevant to the selection of promising sites. On the basis of this knowledge, eight sites were recommended for further consideration. In 2001 a survey project was started on the entire geographical area of the nation. This project was divided into five steps. In steps 1–3, 11 sites were identified as suitable. In step 4 the number of sites was reduced to eight on the basis of accessibility, transport infrastructure, population density, land ownership and public acceptance. The national evaluation was made on the basis of existing information only. No new data were obtained.

In 2003 the preliminary site characterization stage began at six sites, all of which are located in granitoid bodies, in order to reduce the area of existing sites to ~40 km^2 each, and to recommend the optimal area for detailed site characterization. In the Czech Republic, a deep geological repository is expected to be built in granitic rock. Currently all siting activities have been postponed until 2009 by decree of the Government. These six sites will be evaluated, as scheduled, by 2015, and it is assumed that the repository will start operating in 2065.

4.7 Slovakia

In Slovakia three possible alternatives for the back end of the fuel cycle were taken into consideration:

1. SNF could be placed in interim storage for 40–50 years then disposed of directly; HLW would be disposed of in a deep geological repository constructed on Slovak territory.
2. SNF would be shipped and undergo final disposal outside the country.
3. HLW would be reprocessed and stored abroad, then disposed of on Slovak territory.

From the economic point of view, the first alternative, direct disposal after 40–50 years of interim storage, seems to be the most advantageous. The second and third alternatives have not, as yet, been considered but may be given further consideration.

Research and development for a deep geological repository in Slovakia began in 1996. The site selection programme began with a critical review of information (no field investigations) and included a survey of published and archive data on regional geology, hydrogeology, engineering and geophysics. The results identified 15 areas potentially suitable for a deep geological repository in granitic (7), metamorphic (3) and flyschoid (1) formations.

The next 4 years focused on screening via limited field verification and some technical measures. Taking into account the important geological, hydrogeological and mineralogical data, three areas in five localities were determined as suitable sites for the construction of a deep geological repository.

Three localities are situated in granitic rocks:

1. The central part of the Tribec Mountains, 46 km^2;
2. The southern part of the Veporske vrchy Mountains, 78 km^2;
3. The south-western part of Stolicke vrchy Mountains, 24 km^2.

Two are in argillaceous and pelitic formations:

1. The eastern part of the Cerova vrchovina Upland, 87 km^2;
2. The western part of the Rimavska kotlina Basin, 85 km^2.

The Central Tribec Mountains site is an area of granitic rock in the southern Tribec–Zobor block in the Tribec Mountains. The Zobor Massif is one of the largest crystalline complexes in the Western Carpathians. Tectonic deterioration of the site is generally low and thus hydrogeological conditions for a repository seem favourable. The southern part of the Veporske vrchy Mountains and south-western part of the Stolicke vrchy Mountains are adjacent to one other, but belong to two different geomorphologic units, which are divided by a Muran–Divin tectonic line. The Vepor granitic pluton is the largest in the Western Carpathians (~60 km in length) and is a complex pluton, consisting of several granitic rocks. Because of the pluton's size, it has been recommended for further investigations.

The eastern part of the Cerova vrchovina Upland and western part of the Rimavska kotlina Basin belong to different geomorphologic units. From a lithological, structural and spatial perspective, the most suitable host rocks appear to be two lithostratigraphic units: the Szecseny schlier of the Lucenec Formation and the Lenartovce beds of the Ciz formations. These units form the principal mass of the basin filling. The predominant lithology in both formations is a mixture of silstones and claystones. The maximum thickness of the Ciz Formations in the territory of Slovakia is 400–500 m, while that of the Lucenec Formation is 1,300 m.

The project activities are limited, but research and development work is expected to start in the near future. This should lead to a candidate site that is publicly acceptable and a demonstration of the feasibility of the proposed construction, operation and closure of the deep geological repository.

4.8 Romania

In Romania, spent fuel is classified as waste, and government policy aims for direct disposal of SNF around 2050, when the technology becomes commercially available. Romania has Canadian-type reactors, which use natural uranium as nuclear fuel.

It is planned to dispose of these spent fuel elements either in a salt or a hard-rock formation. A long-term safety assessment of a repository has been performed for spent CANDU (CANada Deuterium Uranium) fuel elements in a deep repository located in salt. Results from this report are compared to those of a hypothetical direct disposal of spent light water reactor (LWR) fuel elements in salt.

In the long-term safety assessment of a repository three scenarios have been considered:

1. A subrosion scenario, which represents normal evolution developing over a long period (millions of years). This scenario assumes that, over time, the salt dome is dissolved by groundwater in the caprock region.
2. A human intrusion scenario, which assumes that parts of a 1,000-year-old repository containing RW would be laid bare during the solution mining of a storage cavern.
3. A combined accident scenario, comprising a short overview of the general modelling procedure, which assumes a combination of brine intrusion from the overburden and undetected brine pockets.

The differences between modelling for CANDU and LWR fuel are related to the inventories and temperatures of the waste emplacement fields. Results have been discussed mainly in terms of effective dose. The calculated radiation exposure for the human intrusion scenario are between those for the subrosion and the combined accident scenarios and are of comparable magnitude for CANDU and LWR fuel.

5 Comparison of the Geological Storage of CO_2 and Disposal of Radioactive Waste

There are obvious interconnections between RW disposal and CO_2 storage, and between disposal/storage in the region studied and disposal/storage in general. In a broader sense, the list of interconnections can start with the fact that these materials are produced mainly during power generation. Any kind of technology used to replace them would reduce the need for disposal/storage; moreover, any shift in the balance between nuclear- and fossil fuel-based power generation would alter the type of disposal/storage needed. Here we consider the present-day situation where the replacement of common power-generation technologies with alternatives like solar or wind is still a slow and expensive process. As a result, RW disposal and CO_2 capture and storage have the same importance in terms of keeping all the existing options open.

In the countries of the region, legislation on many different aspects of interim storage and final disposal of RW is well accepted; however, CO_2 storage is a new concept, and it is only because of political decisions (based on long-term climate change issues) and economic influence (CO_2 emission quotas, emission trading) that it has become a possible solution for greenhouse gas reduction in the past few years.

In the region studied, the nuclear industry formerly relied on Russia taking back the spent fuel for reprocessing. Those times have gone, and now most countries are taking steps to establish their own storage and disposal facilities. Each country is in a different phase.

If one looks at the geological storage options considered in the previous chapters, one must conclude that there are different requirements depending on the different geological environments in which CO_2 would be stored and RW would be disposed of. Although both environments should have some kind of seal, the host rocks need to be quite different. In the case of CO_2, they should be permeable, porous or, for example, in the case of aquifers, the chemical solution should hold the CO_2 (for the long term). In the case of RW, the host rock would be part of the seal and should be impermeable; in other words, the opposite. As a result, there is no competition between CO_2 and RW for storage/disposal sites. For CO_2 storage, however, there are economically competitive uses of suitable sites, for example geothermal energy, natural gas storage or coal mining.

The amount of space needed for disposal/storage is also very different. In the case of RW, usually the volume is less than or around 100 t but in the case of CO_2 a few tens or hundreds of million tonnes are generated during 1 year for storage in a single country. In the context of the CEE-8 region this difference has consequences. If one compares the volume produced and the disposal/storage capacities needed for it, there is no obstacle to local solutions, either for RW or for CO_2 (although uncertainty exists with respect to saline aquifers).

Based on the detailed country-by-country discussion of RW disposal and geological storage of CO_2, we summarize some of the key features in Table 3.

In the row 'expected volume' we give comparable figures for RW, where possible. The data refer to the given date or to the end of the lifecycle of the NPPs. We know of no additional benefit resulting from the nuclear waste disposal process, but CO_2 storage can be combined with enhanced oil recovery (EOR) or enhanced coalbed methane (ECBM) production to achieve a more economical solution. Potential CO_2 storage sites should be close to the sources (several hundred in the region); hence, each country must find and exploit its own potential. From the technical and economic point of view one common site for RW at the best location would be the ideal solution. Some countries may not have the resources or the full range of expertise to build their own HLW repository. Countries with small amounts of HLW or with no national solutions in place need to face the problem that deep geological repositories are expensive. These nations also need safe and secure long-term waste management options. There is thus an increasing interest in the concept of shared deep geological repositories in Europe, with a number of countries agreeing to cooperate in implementing a regional facility. From the security point of view (availability, transport, etc.) and public acceptance, this solution can be hard to implement, but it is starting to be discussed. Currently all EU countries, even those with very small nuclear programmes, are under pressure to try to follow purely national programmes, even though the EU and the European Parliament support the concept of regional facilities.

In the period 2003–2005, the European Commission funded a project devoted to pilot studies on the feasibility of shared regional storage facilities and geological repositories for use by European countries. The goal of the second period (2006–2008) was to develop possible practical implementation strategies and organizational structures.

Table 3 CEE-8 region-specific features of radioactive waste disposal and CO_2 geological storage

Key features		Bulgaria	Czech Republic	Hungary	Poland	Romania	Slovakia	Slovenia	Croatia
Expected volume	CO2	510 Mt/yr from point sources (2005)							
	RW	7331 fuel assemblies	3000 tHM	1286 tHM (2017)	No NPP	4170 tHM (2020)	2374 tHM (2039)	620 tHM	No NPP
Estimated storage capacity	CO2	2000 Mt in *depleted hydrocarbon fields*							
		Several tens of gigatonnes in *saline aquifers*							
		No data	700 Mt in *unmineable coal*			No data			
	RW	No practical limitations							
Status of planning	CO2	Pilot projects considered mainly; industrial scale storage demonstration projects are also foreseen in Poland							
	RW	National Strategy (1999)	The Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic (2001)	Elaboration of a national policy for HLW management (2000)	Strategic Government Programme: Radioactive Waste and Spent Nuclear Fuel Management in Poland (1997 to 1999)	Generic studies	R&D for deep geological repositories (1996)	Joint Programme (2004)	
Additional benefits	CO2	EOR ECBM	EOR ECBM (180 billion m3)			EOR ECBM	negligible	EOR ECBM	EOR
	RW	No							
Source locations	CO2	Several 100s larger (>100,000 t/yr) point sources							
	RW	22 NPPs in 8 locations							
Competition with other use	CO2	Natural gas storage, geothermal energy, coal mining							
	RW	No							

Host rock types	CO2	Devonian, Lower Triassic, Middle Jurassic, Valanginian and Eocene	Sediments of various age and lithology	Miocene–Pliocene psammitic sediments	Mesozoic Formations	Miocene–Pliocene psammitic sediments			
	RW	Lower Cretaceous marls, Paleozoic grained granites	Granitic rocks	Boda Claystone Formation	Triassic shale	Generic salt and hard-rock formation	Granitic rocks argillaceous and pelitic formations	Generic location in hard rock	No inf.

ECBM enhanced coalbed methane,
EOR enhanced oil recovery,
HLW high-level waste,
NPP nuclear power plant,
RW radioactive waste,
tHM tonnes of heavy metal

As has been pointed out, geological storage of CO_2 is an emerging technique; however, RW disposal is an existing solution (but not in the region). At the moment none of the countries in the region have an HLW disposal site or a storage site for CO_2, but some countries have a facility for low-level RW or a storage site for natural gas or naturally occurring CO_2. Although the nuclear industry has the support of the public in the region, waste disposal is less welcome near the actual site. Obtaining public support for several tens or hundreds of CO_2 storage sites could be as difficult as solving the technical issues. As there are a number of natural gas geological storage facilities in the region, public acceptance of geological storage of another gas could be easier to obtain.

6 Conclusions

In this study we discussed geological CO_2 storage and RW disposal potential in Bulgaria, Croatia, the Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia. Data of CO_2 point sources were highlighted and possible geological storage locations (aquifers, oil- and gasfields and coalfields) were shown. Based on these reference data, the geological storage capacity is estimated at several decades, if not centuries, for all CO_2 emissions (510 Mt/year) from the larger point sources. These data were compared with the information on RW geological disposal. The total amount of HLW produced during the lifecycle of the existing 22 NPPs is not much more than 10,000 tHM; hence, there are no practical limitations on the quantity that can be disposed of, should a disposal site be built.

We also established that some of the geological sites suitable for CO_2 can be used for other purposes such as geothermal energy production, natural gas storage and coal mining, but these sites are not in competition with suitable RW disposal locations. In the region examined, the majority of the countries are dealing with the problem of HLW disposal. Investigations in all these countries are at an advanced phase, but it will be necessary to wait for several decades before construction of the first deep geological repository in the Central and Eastern European region can be started. As far as CO_2 is concerned, to date only pilot projects are under consideration, although less strict legislation and improved economic benefits, when combined with ECBM production or EOR, could speed up the implementation process.

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