Comparison of the Geological Disposal of Carbon Dioxide and Radioactive Waste in European Russia

Alexey Cherepovitsyn and Alexander Ilinsky

Abstract In this study a review is conducted of natural geological formations in European Russia in terms of their suitability for storage of carbon dioxide (CO_2) and radioactive waste. The geological conditions of European Russia are described, and the regional features and locations suitable for nuclear waste disposal are identified. A scheme is presented of the location of endogenous activity zones (seismic risks, volcanism) and increased radon risk in European Russia. A map showing suitable areas for nuclear waste storage is presented. The clay formations of the St Petersburg region are reviewed as a potential area for radioactive waste disposal. The main characteristics of the geological conditions that have potential as CO_2 storage sites are determined. A conceptual scheme of the CO_2 storage potential in north-west Russia, the most favourable region, is presented. Information about geological structures and depleted oilfields in north-west Russia is provided. The near-term outlook for CO_2 enhanced oil recovery in the oilfields in north-west Russia and the Kaliningrad region is given. A table of comparative assessments of the geological and economic characteristics of radioactive waste and CO_2 storage is also presented in the review.

Keywords Radioactive waste disposal • CO_2 storage • Geological formations • Enhanced oil recovery • Russian Federation

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A. Cherepovitsyn (✉)
Department of Organisation and Management, Saint Petersburg State Mining Institute, St Petersburg, Russia
e-mail: alekseicherepov@inbox.ru; aecherepovitsyn@spmi.ru; oandam@spmi.ru

A. Ilinsky
All-Russia Petroleum Research Exploration Institute (VNIGRI), St Petersburg, Russia
e-mail: alex.ilinsky@bk.ru

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1 Introduction

Russia is large enough to have almost every kind of geological structure and geo-dynamic property, every type of geological formation, and rich deposits of gasiform hydrocarbons, liquid hydrocarbons (oil, groundwater) and hard minerals (metallic and non-metallic). Four geographical locations are considered to be possible places of permanent geological disposal of radioactive waste (RW) and/or carbon dioxide (CO_2):

1. The Nizhnekamsk granitoid massif in the Krasnoyarsk region of Siberia;
2. The Murmansk area in north-west Russia;
3. The Kuril Ridge on Simushir Island, Sakhalin, in the Russian Far East;
4. The Novaya Zemlya (New Land) Island Territory between the Kara and Barents Seas, administered by the Arkhangelsk Oblast.

According to official information, there are no radioactive waste repositories in the Russian Federation today, just 20 temporary storehouses.

Officially, there are also no imports of spent nuclear fuel to Russia from abroad; however, according to ecologists, most of the uranium imported for uranium ore-dressing is still in the country. This RW represents an enormous danger to those employed in the atomic energy industry and to local residents exposed to radiation. Exact statistics on the quantity of uranium stored in Russia are not available. The RW that has accumulated in Russia in recent years has now reached enormous quantities, and there is an urgent need for permanent disposal.

Turning to CO_2, the Kyoto Protocol was the first international instrument to use market mechanisms as a basis for addressing global ecological problems related to greenhouse gas (GHG) emissions and climate change. In response to the economic incentives established by the Kyoto Protocol, most developed countries will reduce their levels of GHG emissions, particularly CO_2, by 5% in 2008–2012, compared with the 1990 level. The Ministry of Natural Resources of the Russian Federation has set the goal of achieving an overall decrease in CO_2 emissions, mainly through energy saving and a switch to modern energy efficient technologies. While the Kyoto Protocol requires efforts to reduce emissions and to implement the rational use of energy and heat, this in no way restrains the economic development of Russia. Furthermore, it is very important for Russia to take advantage of the economic incentives of the Protocol.

The Russian Federation ratified the Kyoto Protocol on 22 October 2004. The CO_2 quota for Russia established by the Protocol was 100% that of the 1990 level. The level of CO_2 emissions in 1990 was 2,360 million tonnes (Mt). Currently, total CO_2 emissions in Russia are 1,572 Mt/year, and specific CO_2 emissions in the power sector are 553 g/kWh (Cherepovitsyn and Ilinsky 2006). Actual emissions in the Russian Federation are thus below quota.

Because of the limited potential of other CO_2 emission reduction options, the concept of CO_2 sequestration by capture and storage in underground reservoirs is gaining ground in Western Europe. Increasing attention is also being paid to this option in the Russian Federation.

The Russian oil and gas industry has a great deal of experience regarding the exploration of subsurface reservoirs for use as spare gasholders. The technologies used in exploring and creating these spare gasholders could also be used for CO_2 storage. Furthermore, injection of CO_2 into oil reservoirs could increase the efficiency of oil recovery and enhance gas recovery.

European Russia, particularly the north-west region, has a large number of oil- and gasfields with only a low level of reservoir development. The geological subsurface of this region is indicative of a large number of aquifers, and the region also has an unutilized supply of gasholders that were created for the storage of gas reserves. All these reservoirs could be used for CO_2 storage (Ilinsky 2005, 2006; Cherepovitsyn and Ilinsky 2006). CO_2 capture and storage thus shows great potential in a region that has a concentration of energy-intensive industries. Moreover, north-west Russia is situated relatively close to Finland, Germany, Poland and other European countries that are potential renters of the subsurface reservoirs for CO_2 storage under the Joint Implementation Mechanism of the Kyoto Protocol.

The problems of CO_2 storage and the technology of sequestration development are in the early stages of scientific research in Russia, and only preliminary estimations of storage potential are currently being conducted. Studies to enhance oil recovery by CO_2 injection were carried out as early as 1970 in the Soviet Union, but were not implemented commercially. There are no natural CO_2 deposits in Russia, but because of the economic incentives of the Kyoto Protocol, interest in such projects has now started to grow.

2 Radioactive Waste Disposal

2.1 Sources of Radioactive Waste in Russia

Radioactive pollution in various regions in Russia, and hence the need to develop RW repositories, is due to nuclear technology-based activities. Statistical data on the radioactive materials and waste that have accumulated in Russia as a result of these activities are presented in Table 1.

The European part of Russia has a huge number of industrial, defence and other enterprises that are potential sources of nuclear danger. Their overall number is close to 10,000, with at least one third being connected to a military or industrial undertaking. In the Murmansk and Arkhangelsk areas there are more than 270 nuclear power installation units, representing 18% of all nuclear power installation in operation worldwide. Many of the enterprises using radioactive materials are concentrated in the region. The most important are the nuclear power stations, shipyards, nuclear-powered icebreaker fleet, Northern Navy, and related infrastructure in St Petersburg and in the Kola (Murmansk) area—in total nearly 4,000 enterprises that use radioactive materials and other sources of ionizing radiation.

The main centres of nuclear power use in north-west Russia, along with the regional geological environment, are shown in Fig. 1.

Table 1 Radioactive waste and the materials that have accumulated in Russia as a result of defence and industrial activities (Shishits 1998).

Stage of nuclear cycle, enterprise, type of waste	Type of material, category of radioactive waste	Weight (t) or volume (m^3) of fuel	Total activity (Ci)	Location
Extraction of uranium and thorium ores	Natural radionuclide LAW	5.6×10^7 t	6×10^5	Tailing dump
Production of fuel- and heat-generating products	LAW	1.6×10^6 t	9.3×10^4	Open storehouses
NPP	Liquid LAW	8×10^4 m^3	3.5×10^3	SLAW on NPP territory
	Solid LAW	5×10^4 t	1×10^3	SLAW on NPP territory
	Hardened waste (bituminous compound)	1×10^4 t	2×10^3	SLAW at St Petersburg NPP and Kalinin NPP
	RW of RBMK (MAW and HLW)	5.325×0^3 t	1×10^9	Storehouse for SNF at NPP
	RW of WWER-440 (MAW and HLW)	9.4×10^2 t	–	Storehouse of SNF at NPP
	RW of WWER-1000 (MAW and HLW)	1.1×10^3 t	–	Storehouse of SNF at NPP
Processing of SNF	RW of WWER-400, BN-350, BN-600, transport reactor (MAW and HLW)	3.5×10^3 t	–	Storehouse of SNF at Mayak plant
	Nuclear waste glass liquid HLW from processing fuel of WWER-440	5.5×10^8 m^3	9.5×10^6	Same as above
Waste from defence programmes	Liquid HLW and MAW	n.a.	5.5×10^8	Capacity storehouses at Mayak plant
	Liquid LAW	n.a.	1.25×10^8	Reservoir No. 9 at Mayak plant
	Solid MAW, LAW: equipment, building and other material	n.a.	1.2×10^7	Storehouse of SNF at Mayak plant
	Liquid HLW, MAW, LAW	n.a.	1.26×10^8	Reservoir atSCE (Tomsk)
			4×10^8	Collectors in deep layers at SCE

(continued)

Table 1 (continued)

Stage of nuclear cycle, enterprise, type of waste	Type of material, category of radioactive waste	Weight (t) or volume (m^3) of fuel	Total activity (Ci)	Location
	Liquid HLW, MAW	n.a.	8.4×10^6	Special KMCE storehouse
	Liquid HLW, MAW, LAW	n.a.	5.0×10^8	Collectors in deep layers at KMCE

BN fast neutron reactor, *HLW* high-level waste, *RBMK* high-power channel-type reactor, *KMCE* Krasnoyarsk mining chemical enterprise, *LAW* low-activity waste, *MAW* medium-activity waste, *NPP* nuclear power plant, *RW* radioactive waste, *SCE* Siberian chemical enterprise, *SLAW* storehouse for low-activity waste, *SLNW* storehouse for liquid nuclear waste, *SNF* spent nuclear fuel, *WWER* water-moderated water-cooled power reactor, *n.a.* not available

The sources of radioactive contamination in the area of study are:

1. Nuclear testing in Novaya Zemlya;
2. Underground nuclear explosions for industrial (non-defence-related) purposes;
3. Nuclear waste deposits;
4. Submerged nuclear ships and the nuclear waste on the Kara and Barents Sea beds;
5. Radioactive fallout from the accident at Chernobyl nuclear power station;
6. Transportation of radioactive cargo (Komlev 1998; Tikhonov 2004).

Near the Lovozerskii and Kovdorskii ore mining and processing enterprises on the Kola Peninsula, the ecological situation is complex (and critical) because of the presence of natural radioactive ore, processed raw materials and finished products. Special action thus needs to be taken to prevent serious accidents. The nearby Loviisa nuclear power station in Finland and Ignalina nuclear power station in Lithuania also represent a potential radiation threat to the Karelia and the Pskov areas (Shishits 1998).

2.2 Geological Disposal Options for Radioactive Waste

Table 2 shows a classification of the mining characteristics of geological environments on a regional basis for European Russia (see also Fig. 1).

The geomechanical parameters of a rock massif govern the geological surroundings and the underground storage that can be used for RW waste. Other properties related to the different components of the sphere (such as ectoplasms, groundwater, the gas-bearing parts of the massif and its geochemical and physical fields) are not as important in determining the technical and mining characteristics of the massif. Nevertheless, they can significantly affect the exploitation of the underground area. The presence of radon, for example, is a serious adverse factor.

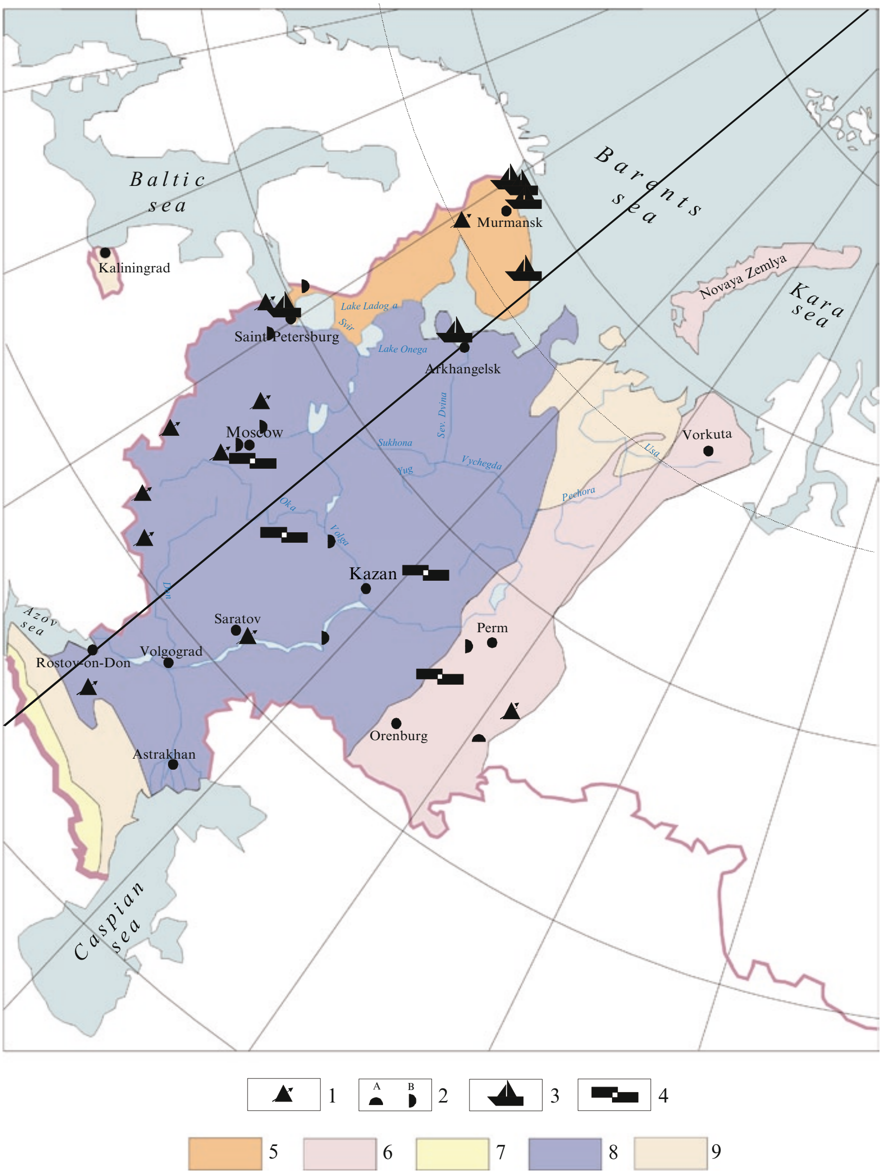

Fig. 1 The main centres of nuclear power use in north-west Russia (1–4) and the regional geological environment (5–9) (*see* Colour Plates). 1 Nuclear power stations. 2 Nuclear reactor: A – technological; B – research. 3 Bases of nuclear fleet. 4 Radiochemical and metallurgical plants. 5 Mountain ranges of Precambrian metamorphic complexes. 6 Folded and magmatic Phanerozoic rocks. 7 Sedimentary and volcanogenic rocks of recent geodynamic active mobile zones. 8 Complexes of lithified sedimentary rocks and vulcanites of ancient platforms. 9 Weakly lithified basic sediments of recent platforms

Table 2 Classification of the mining characteristics of geological environments on a regional basis for European Russia

Engineering geological rock types (pertinent regions in bold)	Mining features geological complex	Evaluation of favourable level of mining-geological complex for RW disposal
Rocky and semi-rocky, in the upper 10–25 m decomposition zones, mainly granitoid **(Republic of Karelia, Murmansk area, part of St Petersburg area, Voronezh area)**	Homogeneous, steady	Suitable
Rocky (in low dislocated zones), semi-rocky, friable non-cohesive (in crush zone), soft cohesive (in Mylonite zones) **(Caucasia, Ciscaucasia)**	Heterogeneous, unsteady	Unsuitable
Rocky (in low dislocated zones), semi-rocky, friable non-cohesive (in crush zone), soft cohesive (in Mylonite zones) **(Ural, Cis-Ural)**	Moderately heterogeneous; moderately steady	Moderately suitable
Friable non-cohesive, soft cohesive, rare semi-rocky **(some central parts of European Russia)**	Heterogeneous, unsteady	Unsuitable

Figure 2 shows the location of endogenous activity zones (seismic/volcanic activity) and increased radon risks. A region's potential for underground storage development is examined in terms of the suitability of conditions, including both internal and external factors. The presence of permafrost in a location is a favourable indicator for nuclear waste storage. Such a location is divided into: (1) the cryolite zone (permafrost); and (2) the area outside the cryolite zone. Within the cryolite zone the impact of negative hydrogeological factors is reduced, but the homogeneity of rocks and their total stability increases. At the same time the danger of radon also decreases. These features need to be taken into account when underground storage development is being considered.

A scheme of the potential for subsurface storage development is presented in Fig. 3.

The most favourable locations for RW disposal are:

1. Areas with cratons of ancient platforms and similar mountain geological complexes at depths of up to 500 m;
2. Outcrops of Precambrian rocks in Phanerozoic folded areas;
3. Areas of platform comprising essentially homogeneous carbonate and clay rocks;
4. Areas of widespread granitoid intrusions with an insignificant display of residual soil (Shishits 1998).

The Baltic Craton is an ideal location for RW disposal. Here, there is a widespread and uniform distribution of granular granite, gneissose granites, migmatite and other formations with a high density and homogeneity, as well as a limited number of recently active breaks. This area's potential is enhanced by its favourable economic-geographical conditions. The slopes of the Baltic Craton's blocked

Fig. 2 Locations of endogenous activity zones (seismic risks, volcanism) and increased radon risk. 1 Cryolite zone boundary. 2 Regions of increased (A) and high (B) radon risk. 3 Seismic risk zones: A – with rare random earthquakes with a magnitude up to 4 (according to the Richter Scale); B–C – with constant earthquakes with a magnitude up to 7 (B) and above 7 (C)

homogeneous, terrigenous and clay formations are also quite favourable for RW storage. Complications within the craton and on its slopes are related to areas of incidental earthquakes and the presence of tectonic breaks which interrupt the homogeneity and stability of the rock massif. On the slopes, the hydrogeological features of sandstone are also present (Smyslov 1996).

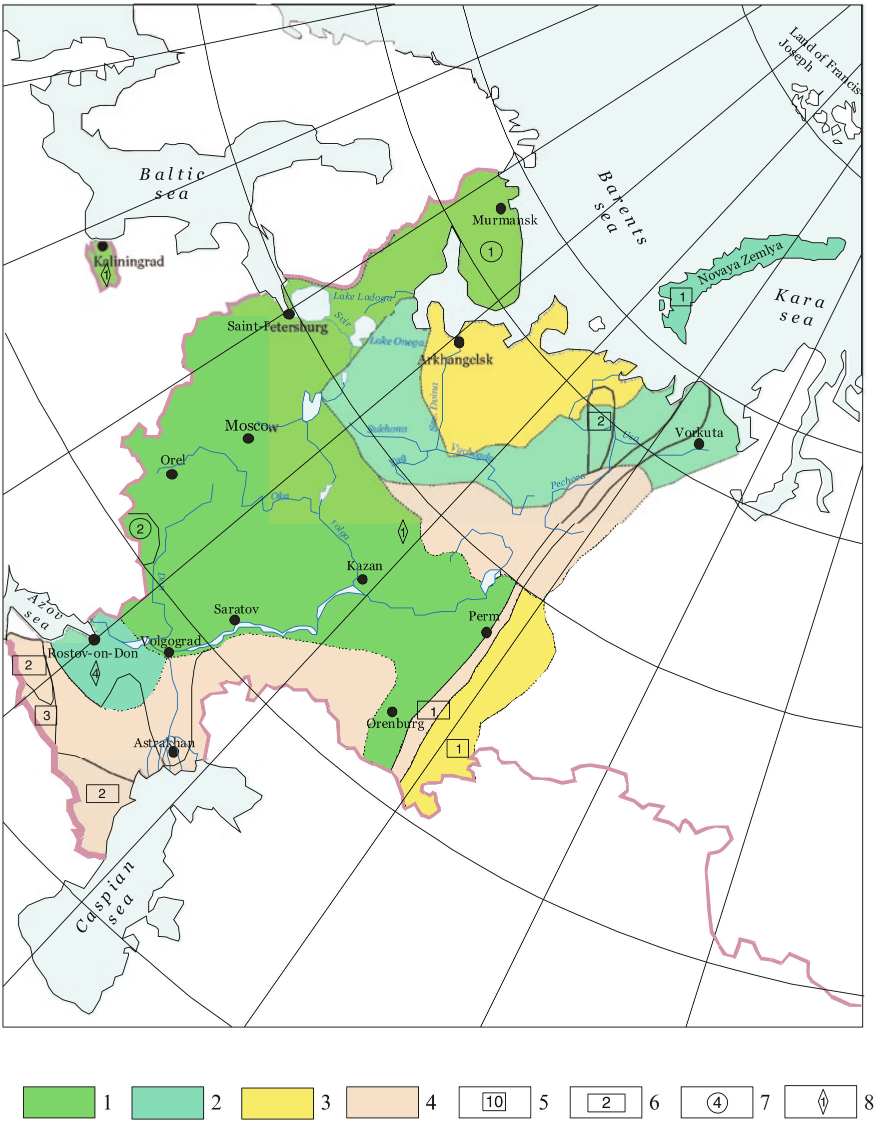

Fig. 3 Map of potential for subsurface disposal site development for radioactive waste (*see* Colour Plates). Coloured areas 1–4, indicating regions: 1 high potential; 2 average potential; 3 suitable areas and regions; 4 low potential. Numbers in geometric shapes: 5 Late Proterozoic Phanerozoic folded areas (*number given in square*) (*1* Urals – Novaya Zemlya; *2* Tieman; *3* Caucasus). 6 Regional deflections (*number given in rectangle*) (*1* attached to Urals; *2* attached to Caucasus). 7 Precambrian folded areas (*number given in circle*) (*1–2* cratons: *1* Baltic; *2* Voronezh Crystal Range). 8 Ancient and recent platforms (*number given in rhombus*) (*4* Skif-Turanic). A dashed line shows the boundary of the respective tectonic structure

The Precambrian crystalline rocks of the Baltic Craton, especially in southern Karelia, are under consideration for underground RW disposal. The following favourable characteristics of the Baltic Craton render it suitable for RW disposal:

- Weak development of surface interstices (pores) of erosion;
- Apparently weak geodynamic activity;
- Low temperatures at the neutral layer level (2–8°C at a depth of 15–30 m), and at greater depths.

In the St Petersburg region, the Lower Cambrian blue clay of the Koporja area can be used for waste disposal. However, this territory is located in one of the country's most active fault zones. Blue clay is an environment with low sorption ability and a high level of vulnerability not only to nuclear irradiation but also to changes in physical, chemical and biochemical conditions. The transformation of these clay sediments under the influence of technogenic factors would adversely affect their isolating potential, allowing the active migration of radioactive nuclides; this, in turn, could cause pollution of the underlying aquiferous stratum used for water supply. As a rule, clay formations and rocks are free from circulating subsurface waters and possess enough plasticity to make them suitable for RW isolation.

Suitable clay formations are abundant in all parts of Russia; their mineralogy, bedding, low permeability and other characteristics make them one of the most promising formations for the construction of RW repositories. The advantages of clay are:

- Insolubility of clay minerals in underground waters;
- Good sorption ability of most clay minerals.

The isolating ability of clay rocks—widely exploited in mining and in the manufacturing of mining equipment—has been widely investigated by the oil and gas industry. However, before storage sites are developed in clay rocks, the following should be considered (Tatarchuk 1997):

- Fluids and hydrated minerals can adversely affect isolation integrity;
- The specific heat conductivity of clay sediments is three to four times lower than that of rock salt. The thermal influence of waste can alter not only the plastic characteristics of clay but also its sorption abilities;
- Clay excavations are difficult to carry out and maintain;
- The volume and circulation rate of fluid passing through the pressure head sites of a clay formation are difficult to determine.

To locate clay formations that can be used as RW repositories, homogeneous clay layers should be sought in favourable mining, geological and tectonic conditions. The most promising formations are deep-water facies pools with homogeneous layers of montmorillonite and montmorillonite-hydromica clay. The main problem is to sustain the capacity of the clay to provide efficient and safe isolation of nuclear waste (Smyslov et al. 2002)

An assessment of the geological criteria fulfilled by the blue clays in the St Petersburg region in terms of suitability for RW disposal are presented in Table 3.

Table 3 Assessment of geological criteria fulfilled by the blue clays in St Petersburg area in terms of suitability for radioactive waste disposal

Level of suitability	Criteria for estimation						
	Tectonic elements	Conditions of accumulation of deposits	Form of clay rock deposit	Depth of bed roof of clay breeds (m)	Capacity of working thickness (m)	Hydrogeological conditions	Seismicity on the MSK-64 scale
Potentially suitable	Platforms and regional deflections	Deep-water sea and coastal sea pools	Homogeneous regional sustained layers of clay and argillites	from 300 to 700 m	>100	Zones of complicated and extremely slowed-down water exchange	<7
Suitable, with restrictions	Platforms, areas of regional deflections, dividing platform and young orogen	Sea, coastal sea and lagoon phases	Homogeneous layers of clay and argillites, local distribution	>300	>100	Zones of complicated water exchange	<7
			Powerful regional sustained layers of clay and argillites	<300	>200	Zones of complicated water exchange	<7
Practically unsuitable	Platforms and regional deflections, intermountain hollows	Continental adjournment of glaciers, lake marsh phases and barks of aeration	Lenses, moraines, alternation of clay with non-tight differences	<300	<300	Zones of active and complicated water exchange	>7

MSK Medvedev–Sponheuer–Karnik

There are also suitable geological formations, including gneiss and granite dome-shaped reservoirs and massifs of Rapakivi granite, on the northern shore of Lake Ladoga in Karelia.

Large granitoid massifs offer the most stable environment for underground RW disposal. When locations are being sought for underground gas storage, monolithic blocks in geological structures are of particular interest. Investigations in north-west Russia have shown that there are monolithic blocks of this kind in many places (for example, the Kola region) (Smyslov et al. 2002).

The Voronezh crystal massif is also a potentially favourable location for RW disposal. This area is characterized by dense homogeneous metamorphosed formations at technically accessible depths and is capped by carbonate rock massifs. Despite the development of Cretaceous and Jurassic sediments on the boundaries of formations with terrigenous structures, the carbonates are characterized by a high level of homogeneity, which suggests that they are of marine origin.

The geological formations that characterize the East European platform are also favourable for RW disposal. Here, the most important areas are those with predominantly clay, sulphate, halogen, and carbonate formations. Even if their capacity is small, they can be used for underground disposal. In some areas these formations lie at technically and economically accessible depths (Ordovician and Silurian carbonate rock mass in north-west Russia, carboniferous deposits in the central part of the Russian Platform, Permian system in the Cis-Ural region, etc.). Complications can arise if there is karst present, especially if the karst is active, as is the case in the Cis-Ural region, and could become more active if the underground area is developed (Smyslov 1996).

Halogen formations are chemical deposits that have accumulated as a result of the evaporation of large volumes of water containing halogen salts. The deposits are evaporites that have precipitated over time in pools, isolated from oceans. Usually the cycle of evaporation begins with sedimentation of dispersed clay, then of dolomite and anhydrite. Most of the evaporation cycle results in rock salt, which frequently includes layers of potash salts. There are huge saliferous reserves in the Near-Caspian hollow. Hydrochloric formations with a wide seam thickness (more than 2,000 m) are widespread over an extensive area.

The characteristics of the saliferous areas of Russia are presented in Table 4.

In the east and north-east parts of the East European platform there are Permian-Triassic terrigene rock masses, characterized by significant lateral heterogeneity and the presence of sulphides with aggressive formation waters. These are harsh environments for concrete and metal.

When areas in the Russian platform are considered for development of underground disposal, in all but a few specific cases the possible lack of heterogeneity of the geological environment must be taken into account, as must the possible difficulties involved in mapping small amplitude breaks.

The Urals should be considered as a region of low to average utility for geological disposal. The need for RW disposal, especially in the Middle and Southern Urals, is indisputable because of the presence of many nuclear installations with a great deal of radioactively contaminated material. In the Urals, carbonate complexes

Table 4 Saliferous areas of Russia (Shishits 1998).

Saliferous region	Type of salt deposit	Depth of burial of salt deposit top (m)
Siberian	Layered	250–1,000 and more
Poyasnino-Knatangskiy	Massive	200–300
Moscow area	Layered	750–1,000
Tuvinian Depression	Layered (trap)	10–700
Dvina-Sukhonskiy Basin	Layered	250–350
Pechora-Kamsky Basin	Dome	100–700
Volga-Ural	Complex structure	25–150
Davidovsky area	Layered	350–450
Kaliningrad Basin	Layered	670–1,000

(coal and Devonian limestones), large granitoid, and gabbroid massifs with weak serpentinization are the most suitable formations for RW disposal.

The Caucasus and Ciscaucasia are unfavourable areas for RW disposal because of the complexity of their geological structure and the high tectonic activity in these regions, as evidenced by high thermal heat flows and seismicity.

Meanwhile in European Russia there are many suitable geological formations for RW disposal. The most important geographical area from the point of view of geology and a developed infrastructure is the north-west region. Research activities are most likely to focus on the geological and other conditions in mudstones, permafrost limestones, and the typical lithologies of north-west Russia.

3 CO_2 Storage

3.1 Sources of CO_2 Emissions

Most (approximately 70%) of Russian GHG emissions are from fuel and energy enterprises. Most of these emissions (up to 70%) come from the power industry; about 30% come from the fuel (heating) sector (Cherepovitsyn and Ilinsky 2006).

The structure of GHG emissions in Russia by economic sector is presented in Fig. 4.

The structure and estimates of CO_2 emissions produced by fossil fuel-fired combustion in the federal districts of Russia are presented in Fig. 5.

The energy sector of the north-west region is shown in Fig. 6.

The installed capacity satisfies the current demand for electric power in the north-west region of Russia. However, most of the generating capacity, as well as the electric mains, are in urgent need of replacement, as investment in renovating and developing them has been extremely low during the last 10 years.

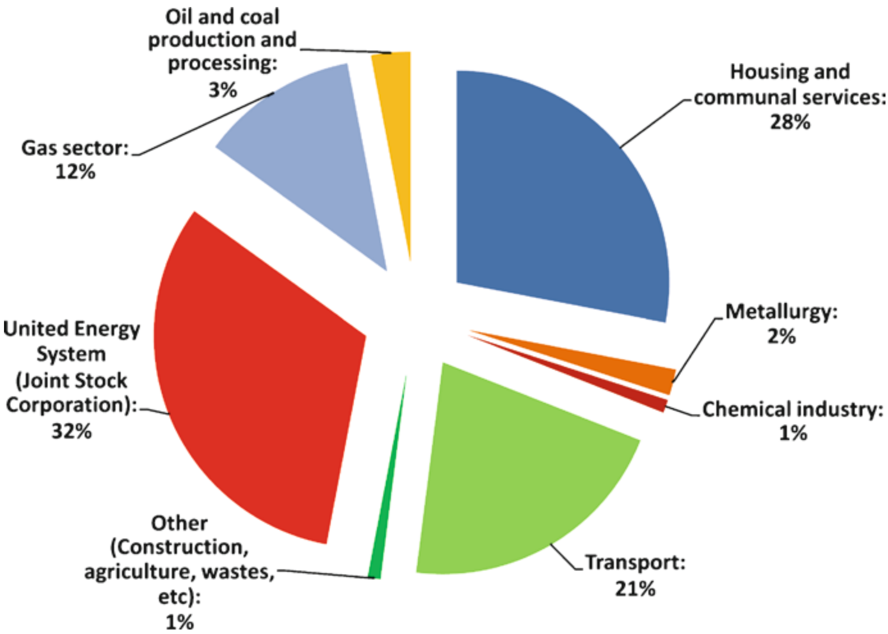

Fig. 4 Structure and estimate of CO_2 emissions in Russia by sectors of the economy

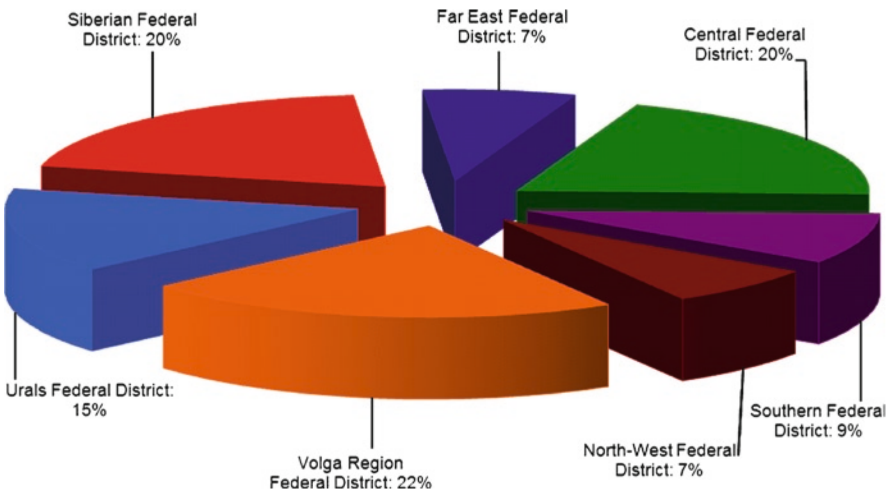

Fig. 5 Structure and estimates of CO_2 emissions produced by fossil fuel combustion in the federal districts of Russia (Source: Ilinsky 2006)

The main sources of CO_2 emissions are shown on the map of the St Petersburg region, which is the region with most developed energy and industrial complexes in north-west Russia and also with the highest CO_2 emissions (Fig. 7).

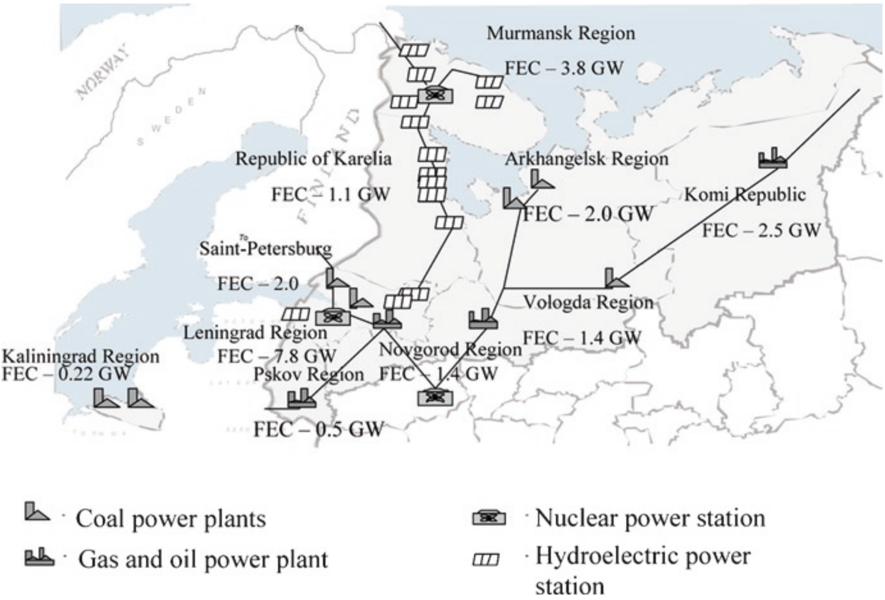

Fig. 6 Energy sector of the north-west region of Russia (Source: Ilinsky 2005), FEC: Full eletric capacity

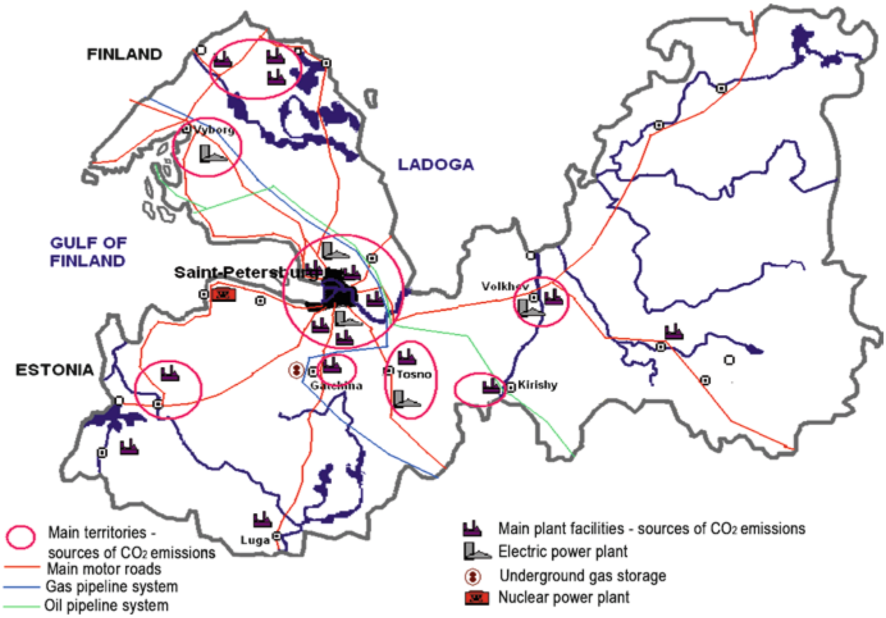

Fig. 7 Main sources of CO_2 emissions in the St Petersburg region

3.2 Geological Disposal Options for CO_2

An estimation of the potential capacity of depleted oil and gas reservoirs for storage of CO_2 has been made based on estimates of the cumulative production and proven reserves of oil and natural gas. The overall capacity for the Russian West Siberian Basin (depleted oil- and gasfield capacity combined) is estimated to be around 177 gigatonnes of CO_2 (Gt CO_2) (Zakharova 2004).

The option of sequestration of CO_2 in unmineable coal seams is still at the feasibility study stage worldwide. However, if this option is to be considered for storing CO_2, account must be taken of the fact that about 82% of the country's coal resources are located in the deposits of western and eastern Siberia, which are quite a distance from the main coal consumption areas. This wide geographic distribution of the areas of CO_2 capture and the potential sink areas can substantially increase the cost of using such reservoirs for CO_2 storage (Zakharova 2004).

In Great Britain, Norway and Germany the main sources of GHG emissions are located 200–500 km from the offshore and onshore oil- and gasfields and aquifers (Stevens et al. 2001; Kjärstad and Johnsson 2004). In Russia, however, the main sources of greenhouse emissions are around 2,000–4,000 km from the disposal sites. It is neither economically nor technologically viable to transport CO_2 to western or eastern Siberia from the Central European part of Russia or from Europe, for that matter.

The north-west region (including Kaliningrad) seems to have the most potential in terms of providing suitable underground reservoirs. This territory is not far from countries that may wish to rent underground CO_2 storage capacity, such as Germany and Poland. However, the geological potential of this territory is estimated by many investigators to be only moderate and further detailed geological studies are necessary.

There are potential storage sites in the north-west around St Petersburg (north and south of Ladoga) and in the Murmansk region (the territories near the Shtokmanovskoe offshore gas condensate field).

Unified Energy Systems, a Joint Stock Corporation, plans to start more than 30 projects in response to the Kyoto Protocol economic incentives. These projects aim to reduce GHG emissions (estimated at more than 20 Mt annually) from the company's power plants. A special Energy Carbon Reserve has been set up to implement these projects, some of which are presented in Table 5.

As can be seen from Table 5, there are no CO_2 capture and storage projects currently under consideration. Problems related to CO_2 emission are not on the agenda in Russia, and development of sequestration technologies is not even at the research stage.

A conceptual scheme of storage potential is represented in Fig. 8. There are four different options for CO_2 storage in north-west Russia.

- CO_2 storage in oil and gas reservoirs with a high level of depletion. At present the level of depletion of the oilfields in the region is 27%. From the economic standpoint CO_2 storage could have an additional effect in terms of utilization of CO_2 for enhanced oil recovery (EOR) methods in the oilfields; however, this is not yet used in Russia.

Table 5 Carbon projects chosen for investment by the Energy Carbon Fund of Russia at power stations in the north-west region of Russia

No	Project and initiator	Project title	Project status	Project cost in million €	CO_2 emission reduction in million t/year
1	Kaliningrad CHP-2 JSC UES	Greenfield construction of 900 MW generation capacity	Feasibility study	532	1.0
2	North West CHP JSC UES	Construction of an additional 900 MW generation capacity	Feasibility study	230	n.a.
3	Pskov TPP JSC UES	Construction of an additional 215 MW generation capacity	Feasibility study	32.5	n.a.
4	Kirishi TPP JSC UES	Transition of boilers No. 1 and 2 (co-generation part of Kirishi TPP) from heavy fuel oil to gas	Project proposal	3.76	0.130

For further information, see website of Energy Carbon Fund of Russia (http://www.reeep.ru)
JSC UES Joint Stock Company Unified Energy System of Russia, *CHP* combined heat and power, *TPP* thermal power plant, *n.a.* not available

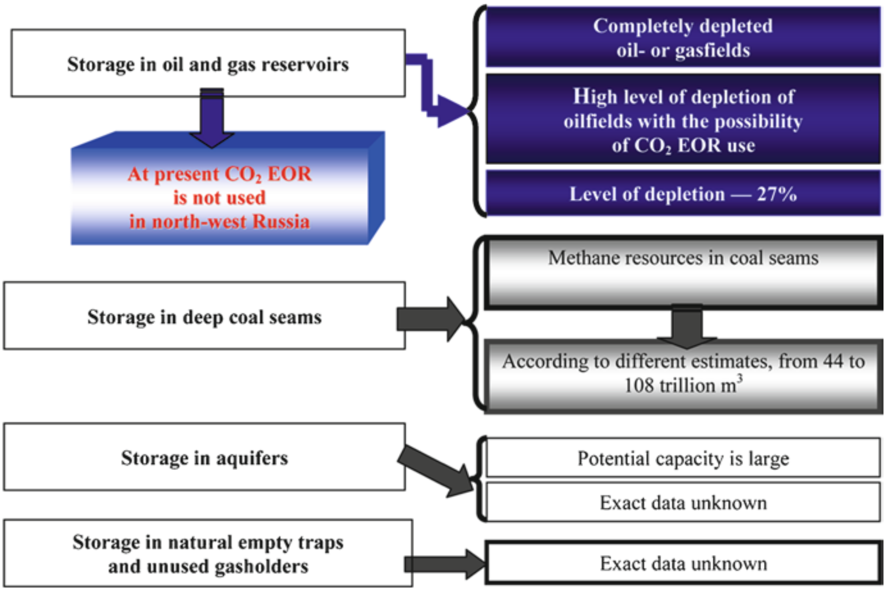

Fig. 8 Conceptual diagram of CO_2 storage potential in north-west Russia

- CO_2 storage in deep coalbeds. The methane resources in coalbeds in the north-west are estimated at 44–108 trillion m^3: this storage method could also be used for enhanced coalbed methane (ECBM) recovery in these coalfields.
- CO_2 storage in aquifers. According to preliminary estimates, this method has a very large potential; however, exact data for Russia are presently unknown.
- CO_2 storage in natural empty traps and unused gasholders. There are a few gasholders in the region, but information regarding their capacity is classified. Thus, currently, the most probable method of CO_2 storage in the north-west region of Russia is storage in oil reservoirs and CO_2 utilization for EOR (Cherepovitsyn 2005, 2006).

According to Cherepovitsyn and Ilinsky (2006), three possible areas for GHG storage in the north-west region of Russia are:

- Timano-Pecherskaya oil and gas province (geological data show initial reserves to be approximately 9.8 Mt oil equivalent (Mtoe));
- Continental shelf area (initial reserves of 3,698 Mtoe);
- Off-shore area (initial reserves are 6,072 Mtoe).

Only sites with an average porosity of not less than 10–15% for normal conditions and not less than 5% for fractured rocks can be used for future underground CO_2 storage. For an aquiferous stratum, the average permeability should be not less than 0.15 μm^2. Permeable beds in quaternary sediments are characterized by considerably better flow capacities.

Aquifers to create underground CO_2 storage repositories require the following qualities:

- Presence and integrity of structural or screened traps;
- Establishment of geological peculiarities of the trap and main characteristics of geological objects, including caprocks, within the exploration area;
- Acquisition of hydrogeological data on all aquifers to determine their sealing properties.

The following geological requirements for reservoirs already exist:

- Collectors should have capping strata of impermeable plastic or hard rocks;
- Caprocks should be homogeneous and their thickness not less than 2–6 m for depths of 600 m and from 4 to 5 m for depths over 600 m;
- To guarantee the long-term operation of CO_2 storage, additional interlayers with sealing properties should be present in the formations;
- Within the calculated contour of the future CO_2 storage there should be no tectonic faults that could lead to a decrease in impermeability of the main and reserve capping rocks;
- Permeability of caprocks should not exceed 10^{-10} mD.

An alternative method of calculating the potential CO_2 storage capacity in the CO_2 fields is the Reidulv Bøe methodology (Bøe et al. 2002).

Table 6 CO_2 storage capacity in oilfields in north-west Russia

Oilfield	Cumulative production (Mt)	Min total capacity of CO_2 storage (kt)	Max total capacity of CO_2 storage (kt)
Komi Republic (onshore)	393,220	271,291	349,176
Nenetsky AA (onshore)	56,850	39,222	50,482
Kaliningrad Region (onshore)	31,030	21,408	27,544
North-west Russia (total)	481,100	331,921	427,202

The primary data required in this case are:

- Initial recoverable resources of oil;
- Initial recoverable resources of natural gas;
- Minimal and maximal values of underground oil density (kg/m^3);
- Minimal and maximal values of underground CO_2 density (kg/m^3).

The CO_2 storage capacity in oilfields in north-west Russia is represented in Table 6. Calculation of reservoir capacity for storage of CO_2 was carried out in this investigation using the Reidulv Bøe methodology.

CO_2 EOR needs to be introduced in Russia for the following reasons (Cherepovitsyn and Ilinsky 2006):

1. To assess the potential for joint implementation in CO_2 EOR processes;
2. To determine the main aspects and size of the CO_2 EOR market, providing details for each oil producing region;
3. To investigate the range of prices for industrially captured CO_2 that can be afforded by oilfield operators, bearing in mind that the price would include not only the volume of CO_2 purchased, but also the distance to the oil basin and the quality of the oilfield;
4. To investigate opportunities for establishing public–private partnerships that would encourage large-scale joint CO_2 EOR and CO_2 storage activities in each of the major oil basins, including policies, incentives, improved CO_2 EOR R&D/ in situ demonstration projects and 'zero emission' hydrocarbon processing plants.

Oil and gas reservoirs, aquifers and unmined coalbeds are all geological structures with the potential for CO_2 storage. The geographical distribution of potential storage formations differs from that of RW deposits. However, the priority is given to the north-west region with its rich reserves of hydrocarbons in the Timano-Pechera province and the Kaliningrad area. EOR processes are the only way that there can be large-scale utilization of CO_2 and where CO_2 acquires a positive economic value. The total potential capacity of CO_2 storage sites in north-west Russia (depleted oil- and gasfields) is estimated to range from 331.9 to 427.2 Mt.

4 Comparative Assessment

The main criteria for and a comparative assessment of RW disposal and CO_2 storage are presented in Table 7 in terms of the geological features of European Russia.

4.1 Disposal of Radioactive Waste

The isolation of RW is based on the principle of the creation and use of a natural engineering system that protects against ionizing radiation via a basic barrier that is poorly permeable in a seismically stable geological environment.

Many types of geological formation and rock compositions can be considered as potentially suitable environments for RW isolation. The most important parameters of these environments are: size, homogeneity, thickness, structural and hydraulic characteristics, physical and chemical properties, mineralogical structure and petrological features, physical, thermal and mechanical characteristics, possible geochemical reactions, etc.

The selection of geological formations for RW disposal in European Russia is a complex scientific and practical problem. Many types of waste produce a great deal of heat over long periods of time and possess a large number of aggressive chemical and radiation properties. In an underground disposal site, they can thus fundamentally change over time and, in due course, the original properties of a massif can be transformed or destroyed.

In European Russia there is a large potential for developing underground RW disposal sites.

Assessment on a regional basis of such underground areas is as follows:

- Baltic Craton (Murmansk region, Republic of Karelia, Part of St Petersburg region): favourable;
- Voronezh Crystal Massif: favourable;
- East European (Russian) Platform (west and north-west): favourable;
- Russian Platform (East and North-East): unfavourable;
- Northern Caucasia and Ciscaucasia: unfavourable.

4.2 Disposal of CO_2

The highest potential for geological CO_2 storage can be found in:

- The Timano-Pechera oil and gas province (Komi Republic and Nenets Autonomous Area);
- The Kaliningrad area.

Table 7 Comparative assessment of geological conditions for favourable disposal of CO_2 and radioactive waste

Comparative criteria	CO_2	Radioactive waste
Type of geological formation	Depleted oil- and gasfields, aquifers, deep coalbeds	Many types of rocks: clay formations, halogen formations, sandstones, basalts, tuffs
Disposal capacity	High (in Russia approximately 177 Gt CO_2 in oil and gas reservoir)	High, but Russian nuclear power industry produces only a relatively small amount of radioactive waste
Caprocks	Caprocks should be homogeneous and their thickness no less than 2–6 m at depths of 600 m and 4–5 m at depths over 600 m	Magmatic rocks > 500 m Halogen formations 75 m Layers 200 m Domes, clay formations > 100 m
Permeability of caprock	→ Min. Permeability of capping rocks should not exceed 10^{-10} mD	→Min.
Hydrogeological condition	Acquisition of hydrogeological data on all aquifers with determination of their sealing properties	Zones with extremely slow water exchange
Depth	In most cases, over 600 m	More than 300 m
Seam pressure	Pressure of ground waters > intrinsic pressure of CO_2	
Tectonic breaks, seismicity	→ Min.	→ Min. seismicity on the MSK-64 scale to be < 7 (less than 6.2 on the Richter scale)
Retention time	→ Max., more than 5,000–10,000 years	Max.
Location	Oil and gas province in north-west Russia	Murmansk region, Republic of Karelia, Part of St Petersburg region, Voronezh Crystal Massif
Provision index of transport infrastructure	→ Max. (well-developed network of pipelines)	Depends on development of infrastructure (road, container shipment—development of port area, railway)
Distance from points of emission source to disposal sites	→ Min. (30–1500 km in north-west Russia)	Not so important: depends on safety of transport means
Transport infrastructure	Absent for CO_2 transportation, but good prospects of being developed in the future	Good developed transport infrastructure in European Russia
Storage cost	Worldwide analogue	Exact data are unknown

(continued)

Table 7 (continued)

Comparative criteria	CO_2	Radioactive waste
Economic benefits	Additional economic value with use of CO_2 EOR Project of joint implementation in context of Kyoto economic incentives	Economic incentives of radioactive waste disposal need a legal basis
Public acceptance	Low level of knowledge about CO_2 sequestrations processes	Some civil society organizations occasionally raise issue of nuclear waste disposal and safety

MSK Medvedev–Sponheuer–Karnik

There are many oil- and gasfields situated in these two areas, including ones with a high level of depletion, and possible aquifers. The unmined coal seams of the Pechera coal basin (Komi Republic) have a huge storage potential.

4.3 Viability of Geological Storage in Russia Today

In the north-west and other regions, the participation of enterprises in joint implementation projects, including CO_2 storage, is fairly limited. The main reason is the absence of a Russian state register for GHG emissions. Another reason is the absence of a normative-legal base regulating the economic incentives of the Kyoto Protocol (Ilinsky and Cherepovitsyn 2005).

The economic success of CO_2 storage projects in the north-west region would be dependent on greater use of EOR. Research shows that there are depleted oil- and gasfields available for storage in the Komi Republic and the Kaliningrad area. The distances from sources of industrial emissions range from 30 to 1500 km to the Komi fields and from 20 to 50 km to the Kaliningrad fields.

It must be noted that the new Energy Strategy of Russia to 2030 recommends an accelerated introduction of innovative industrial technologies related to EOR, with gas, water-gas, thermogas and thermal methods being the priorities. Comparative analysis shows that one of the most effective and rational technological processes from the point of view of energy and resource saving, and in terms of increasing the oil recovery ratio, is stimulation of petroleum reservoirs by gas injection, including injecting CO_2.

To transport CO_2 to the injection sites, the opportunity to use existing, dedicated gas pipelines (for example, in north-west Russia) must be considered. If new pipelines have to be built, the cost of a CO_2 sequestration project will multiply.

For economic evaluation of RW disposal, there is a need for institutional and legal regulations to encourage nuclear enterprises to implement RW disposal projects. Private–state partnerships are needed for similar projects. It is envisaged that both economic and ecological risks would be shared among the participants through a risk insurance fund. This will promote RW disposal in geological formations and encourage investment in such projects. However, it is unlikely that a satisfactory method of accounting for risk in nuclear power will be found unless greater social, economic and environmental efficiency is achieved.

Public organizations and the population in general have insufficient information about the problem of CO_2 storage. To date, no CO_2 sequestration projects have been carried out. We would thus anticipate that societal and public acceptance in Russia of CO_2 storage will take a long time to achieve (Ilinsky and Cherepovitsyn 2006).

The problem of RW disposal is discussed on occasion by environmental organizations. It is assumed that Russia imports RW and that RW disposal sites already exist. However, no confirmation of this is forthcoming from state bodies, and there are no discussions held on this issue at a national level.

5 Conclusions

This chapter is one of the first attempts to define the regional geological conditions for RW disposal and CO_2 storage in Russia. Questions regarding RW disposal in geological formations have been studied by Russian scientists for a long time. However, according to official sources there are no permanent RW disposal sites in Russia, just 20 temporary storehouses.

Meanwhile, in European Russia there are many geological formations that could be used for RW disposal. The north-west region is a priority area not only from the geological standpoint but also in view of the region's developed nuclear infrastructure. Possible future research directions would include a study of geological and other conditions in mudstones, permafrost limestones and the typical lithologies of north-west Russia.

The geological structures of the part of the Baltic Craton in the Murmansk area are suitable for RW disposal. These structures, for example, the Pechengskaya area, lie in an area that has a developed transport infrastructure and is close to sources of radioactive pollution. The permafrost rocks of the Novaya Zemlya archipelago are also interesting geographically for RW disposal. Favourable areas for RW disposal are the crystalline rocks of the Voronezh Craton and some of the halogen formations of the East European platform.

No economic information on the problem of RW disposal in geological formations is available. Any financial investment for research work will be initiated by the state. The participation of private investors in private–state partnerships is unlikely. The state will also establish what levels of economic profitability are necessary for RW disposal projects in geological formations. Public acceptance of long-term RW disposal in geological formation is very low. It remains so because information on this issue is inaccessible.

To date, hardly any scientific research on CO_2 storage in geological formations in Russia has been conducted. Oil and gas reservoirs, aquifers and unmined coalbeds are the types of geological structure that can be used for CO_2 storage. The geographical distribution of potential CO_2 storage formations differs from that of RW storage. However, the priority areas for both are the north-west province of the Timano-Pechora region, with its rich reserves of hydrocarbons, and the Kaliningrad area.

At present the actual CO_2 storage capacity is known only for oil- and gasfields. Some regions, like Kaliningrad and the Komi Republic, have a high level of depleted oilfields. CO_2 EOR is not currently used in oilfields of north-west Russia.

The total potential capacity of CO_2 storage sites in north-west Russia (depleted oil- and gasfields) is estimated to range from 331.9 to 427.2 Mt. In view of the current level of CO_2 emissions and existing fuel and transportation costs, CO_2 capture and sequestration technologies are a possible option for reduction of CO_2 emissions in Russia only after 2012–2015.

The development of CO_2 sequestration technologies and innovative CO_2 storage projects will be based on large-scale use of the Joint Implementation Mechanisms of the Kyoto Protocol. If the development of EOR technologies, including the gas methods designated in the Energy Strategy of Russia to 2030, are prioritized, this will stimulate innovative projects of CO_2 storage in north-west Russia.

The amount of information concerning CO_2 sequestration in Russia is very low, with practically no scientific articles or any other literature at all on this issue. There is as yet no indication as to what public opinion might be with regard to CO_2 sequestration. Investment by the government and various scientific funds are needed to foster research into the issue of CO_2 storage.

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