Bełchatów open-lignite mine, Poland. Photo by I. Śmietańska.

Chapter 16 Applied geology

Authors
Andrzej Gąsiewicz (PGI), Christian Bos (TNO), Grzegorz Czapowski (PGI), David Evans (BGS), Wojciech Górecki (University of Science and Technology, Kraków), Marek Hajto (University of Science and Technology, Kraków), Doug Holliday (BGS; retired), Sam Holloway (BGS), Neil Jones (Saudi Aramco), Jacek Kasiński (PGI), Beata Kępińska (University of Science and Technology, Kraków), Leslie Kramers (TNO), Ben Laenen (VITO), Graham Lott (BGS), Ad Lokhorst (Private), Anders Mathiesen (GEUS), Franz May (BGR), John Rowley (BGS), Sandro Schmidt (BGR), Robert Sedlacek (State Authority for Mining, Energy and Geology, Geozentrum), Peter Seibt (GTN Neubrandenburg), Erik Simmelink (TNO), Radosław Tarkowski (Polish Academy of Sciences), Barbara Uliasz-Misiak (Polish Academy of Sciences), Jan Diederik van Wees (TNO), Ton Wildenborg (TNO), Markus Wolfgramm (GTN Neubrandenburg) and Theo Wong (TNO; retired)

Bibliographic reference
Gąsiewicz, A., Bos, C., Czapowski, G., Evans, G., Górecki, W., Hajto, M., Holliday, D.W., Holloway, S., Jones, N.S., Kasiński, J.R., Kępińska, B., Kramers, L., Laenen, B., Lott, G.K., Lokhorst, A., Mathiesen, A., May, F., Rowley, W.J., Schmidt, S., Sedlacek, R., Seibt, P., Simmelink, E., Tarkowski, R., Uliasz-Misiak, B., Van Wees, J.D., Wildenborg, A., Wolfgramm, M. & Wong, T.E., 2010. Applied geology. *In:* Doornenbal, J.C. and Stevenson, A.G. (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 283-299.

1 Introduction

The increase in energy demands and the decrease in hydrocarbon resources have stimulated better use of geological information in both traditional and new applications. Previous chapters have described the importance of hydrocarbon resources in the SPB. This chapter summarises the state and development of the exploitation of coal, lignite and geothermal energy, as well as the use of hydrocarbon fields for underground gas storage (UGS). The latter includes the emerging potential for CO_2 storage in geological structures, an application which has developed significantly during the last decade.

Whereas the traditional role of coals in producing energy is gradually declining for various reasons (at least in some European countries), the use of lignites appears to be guaranteed for the near future due to the large resources and relatively easy access. Economically, the most important solid-fuel mineral resources in the SPB area are the abundant Neogene lignite deposits of Germany and Poland. The lignites are used as a basic energy resource for heating in pit-mouth power plants, although their excavation and exploitation has had significant environmental impact. The potential for coal to be used as a source of oil and gas has recently focused on the use of coal-bed methane and underground coal gasification.

There are various geothermal systems with very different extent and resource potential within the SPB area. The most important are found in sedimentary basins where they are water-dominated systems with temperatures below 150°C and so are essentially low-temperature or low-enthalpy, static (or stagnant) systems. Closed geothermal systems occur in various stratigraphic aquifers up to a few kilometres in depth. Geothermal energy has several benefits, among which the most important are availability of a long-term sustainable energy supply of consistent quality, and the considerable contribution to the reduction of greenhouse-gas emissions. The systems are extremely well suited as a base-load energy supply for heating purposes and the security of supply of underground heat.

According to current global environmental policies (including EU directives), human activities must reduce the amount of CO_2 they release into the atmosphere. One of the approaches that can be used to reduce emissions is storage of CO_2 in deep geological reservoirs (essentially below 1000 m); among which oil and gas reservoirs and aquifers are the most suitable. Although there is a high demand for this type of environmental technology and increasing knowledge of the process, the consequences of storage are not yet fully understood. For example, in Germany, deep underground brines are classified as water according to the Federal Water Law (Wasserhaushaltsgesetz) and therefore protected against the injection of substances that have adverse effects on the water's composition; this may give rise to problems with CO_2 storage should it escape from the reservoir into shallower formations. The possibility of CO_2 leakage from underground repositories to the land surface or sea bed is also a potential environmental problem. It is necessary therefore to assess the integrity of long-term installations and the caprock of the reservoir (i.e. possible enlargement of existing fractures, new cracks and fault reactivation due to pressure), and to model interactions between the CO_2 and surrounding rocks over time (e.g. Wilkinson et al., 2009) in order to prevent leakage and ecosystem damage.

The actual amount of CO_2 that can be injected into an aquifer further depends on the maximum storage pressure permitted, reservoir management and the design of the well. Realistic estimates of national aquifer-storage capacities will also have to consider other, as yet unknown, geotechnical, economic or legal conditions, which will probably further reduce the volumetric capacity (May et al., 2005). Looking ahead, it is possible that artificial carbon sinks will only mitigate current climate fluctuations and support natural sequestration of CO_2 by the most effective biotic and oceanic surface-water systems.

Gas is stored underground primarily in depleted hydrocarbon fields, salt caverns that have leached within thicker salt series (i.e. in salt domes and diapirs and stratiform salt deposits), and in deeper aquifers with good reservoir properties and seals. The numerous Lower Permian (Rotliegend) and Zechstein depleted gas/oilfields, salt domes and stratiform salt deposits are particularly important in the SPB area. In cases where abandoned hydrocarbon-exploitation infrastructures are used for UGS, the environmental impact is minimal. However, questions remain, such as whether or not the brine from cavern construction represents industrial waste, and the impact of fluid injection into rock pore spaces. As a result, re-used reservoirs require permanent monitoring. Monitoring at a well located in a sand stringer 15 m above the gas reservoir at Stenlille in Denmark (see **Figure 16.30**) indicates no sign of gas leakage since the start of gas injection in 1989 (Øbro, 1989). Regular analysis of shallow groundwater above the injected reservoir also indicated that there has been no gas leakage (Laier & Øbro, 2009). In the Netherlands, there is no evidence of fault re-activation due to cyclic pressure fluctuations or of any impairment of the zonal isolation around the casing string (cement bond) at re-injected gasfields. In places where salt caverns are used for UGS, the shape of the cavern may change during UGS operations.

2 Coal and lignite deposits

2.1 *United Kingdom*

Location and geological settings
The main coal-bearing successions within the UK part of the SPBA area are Carboniferous in age (see Chapter 6; Figure 6.17); the Westphalian successions are the most extensive and thickest (Cameron, 1993; Knight et al., 1996; Besly, 1998) (**Figure 16.1**). There are relatively insignificant coals in the Middle Jurassic succession. Dinantian coals are restricted mainly to the Mid North Sea High and the Berwick-upon-Tweed area of north-east England. The main Dinantian coals are often quite poor in quality and are found in the Scremerston Formation, where they are up to a few metres thick with a maximum cumulative thickness of 21.3 m (Knight et al., 1996) and comprise up to 5% of the formation (Fowler, 1926; Cameron, 1993). Late Dinantian coals are thin and also of low quality, typically up to 1 m thick and comprising less than 1% of the succession (Cameron, 1993). Thin Namurian coals are limited to the southern edge of the Mid North Sea High and are 0.5 to 5 m thick with 10 to 20% total organic carbon (TOC) content (Bailey et al., 1993) and a maximum cumulative thickness of 29.6 m (Knight et al., 1996). The Westphalian coals in the East Pennines dip gently eastwards to the North Sea coast and beyond; at Saltfleetby, the base of the Westphalian occurs at about 2300 m depth (Hodge, 2003). The best coals are of Langsettian to Bolsovian age and generally the thickest coal onshore is the Barnsley-Top Hard. The cumulative thickness of coal seams more than 0.4 m thick is between 19 and 22 m; several seams are more than 2 m thick in many areas of the East Pennines.

Coals are found offshore at depths between 2000 and 4500 m. In the Sole Pit Trough area, Westphalian rocks are up to 1000 m thick and coals form 5% and 8% of the Langsettian and Duckmantian to Bolsovian successions respectively (Bailey et al., 1993) and have a total thickness of 74.4 m (Knight et al., 1996). Thin coals (<0.5 m thick) are found in the Middle Jurassic Ravenscar Group to the south-west of Whitby and offshore; they are also thought to occur in the West Sole Group (Knight et al., 1996).

Main characteristics, origin and type
Most Westphalian coals in the East Pennines and Northumberland-Durham areas are humic. They have characteristically high-volatile bituminous rank with relatively low *in-situ* methane contents (1.5-5.9 m^3/t; Creedy, 1991). In Northumberland-Durham, the coals are typically of medium-volatile bituminous rank with low methane content (1.3 m^3/t) (Creedy, 1991; Baily et al., 1995). The coals from the Dinantian Scremerston Formation are also bituminous in rank (Fowler, 1926). Within the Silverpit area, the coals range from high- to medium-volatile bituminous rank, the higher ranks are found in the centre of the Sole Pit Trough (Cornford, 1990). The Scremerston Formation coals formed in a low-relief, marine-influenced, coastal plain traversed by river channels (Collinson, 2005) whereas Westphalian coals have less marine influence and are thought to have been deposited in mires associated with a lower alluvial-plain or upper delta-plain setting (Guion & Fielding, 1988).

Mining
Coals have been extracted from both opencast and deep mines. Opencast mines are found mainly along the western margins of exposed coalfields whereas deep mines are located to the east. There are three deep mines currently working in the Yorkshire-Nottinghamshire coalfield, but none in Northumberland-Durham. Longwall-retreat mining methods are used to access the coal (IMC, 2002). Methane is emitted from coals during mining and, after the mines close, the gas is collected and used for power generation (Kershaw, 2005).

Figure 16.1 The coalfields and coal-resource potential of the UK.

Economic importance
In 2005, coal accounted for about 17% of the total energy used in the UK and was the third most important source of primary energy after gas (40%) and oil (33%). Coal extraction is increasingly reliant on opencast mines. The East Pennine and Northumberland-Durham coalfields continue to be of economic importance although production has reduced significantly during the last decade. There are poor prospects for the development of any new mines. Deep-mined coal in the East Pennines peaked in the 1950s to 1960s at just over 80 million t/y (Allen, 1995) and now stands at about 5 million t/y (**Figure 16.2**) (source: Coal Authority). The estimated coal reserve is in the order of 1000 Mt in an area of about 1300 km^2 in the East Pennines (Allen, 1995). The coals in the southern North Sea are excluded from this total due to economic and technical limitations. There is potential to use coal from coal-bed methane (CBM) and underground coal gasification (UCG) (**Figure 16.1**) (Holloway et al., 2005; Jones et al., 2005) although CBM prospects are thought to be poor due to the relatively low seam-gas contents and uncertainty about the permeability of the coals. There are possibly areas that are suitable for UCG in the East Pennines and Northumberland-Durham areas (Jones et al., 2005).

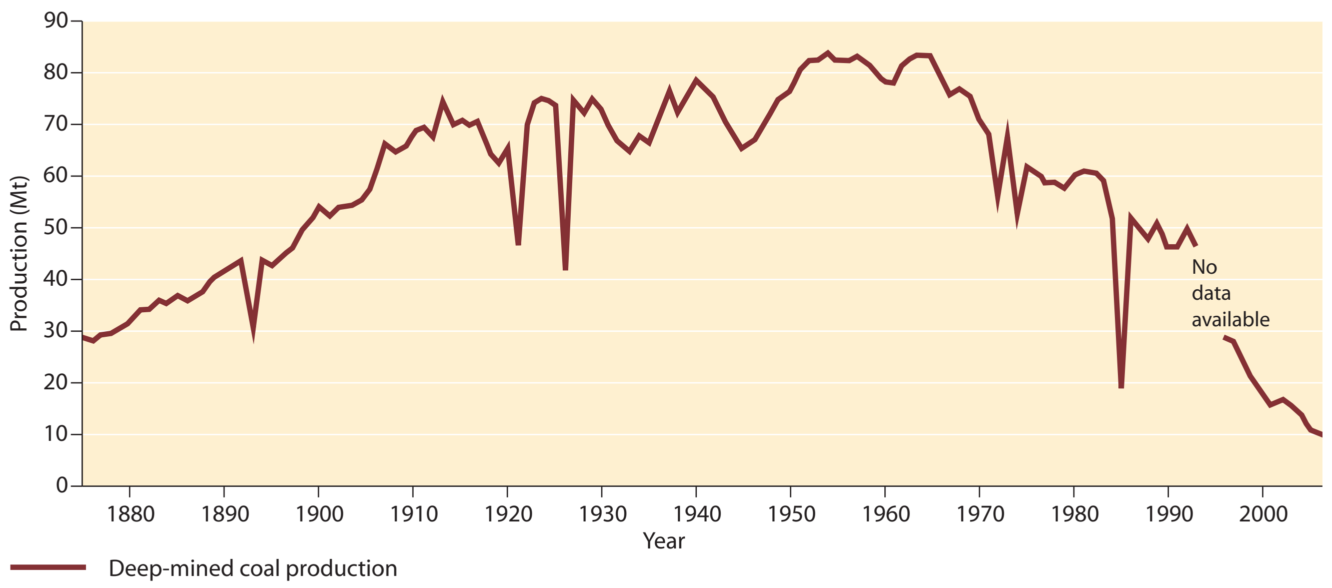


Figure 16.2 Deep-mined coal production from the East Pennines area (modified and updated from Allen, 1995).

Regulations and licensing

UK Government policy for the coal industry is controlled by the Department of Energy and Climate Change (DECC). The DECC also supervises the regulations established by the Coal Industry Act 1994 and act as sponsors of the Coal Authority. The Coal Authority, a Non-Departmental Public Body, owns the UK's coal resource and issues licences to mining operators for the exploration and extraction of coal. The Authority also monitors licence operations and undertakes annual inspections of all operational mines and opencast sites. Many other regulations also apply, such as those imposed by the Health & Safety Executive, and the Town and Country Planning Act 1990. The Mineral Planning Guidance Notes 3 (revised) of March 1999 set out the planning policy for coal in England.

2.2 Belgium

Location and geological settings

The Namurian to Westphalian coals of Belgium occur in two separate basins: the southern Walloon Basin and the northern Campine Basin (**Figure 16.3**). The Walloon Basin has several mining districts; the most productive are located in the Hainaut Province. In addition to the coal deposits along the Sambre-Meuse axis, there are a few small coalfields in the Dinant and Theux basins (Delmer et al., 2001). The Walloon coal basin is located in the Namur-Verviers Synclinorium at the front of the Variscan mobile belt. The synclinorium consists of both autochthonous and allochthonous beds affected by Variscan folding and faulting. The southern limit of the mining districts is formed by the Midi-Eifel Fault, along which Devonian rocks are thrusted over the parautochthonous coal basin, obscuring its southern limit (**Figure 16.3**) (Delmer, 1997). The Westphalian coals of the Campine Basin (Antwerp and Limburg provinces) are overlain by Mesozoic and Tertiary rocks. The basin is cross-cut by north-north-west-striking normal faults that were intermittently active from Carboniferous times until the present day. The faults form the south-western border of the Roer Valley Graben. This system is cross-cut by local subordinate north–south to north-east–south-west-trending thrust faults, which intersect with the north-north-west-striking faults that form the elongated fault blocks. The blocks are gently tilted (5 to 10°) towards the north-north-east (where Silesian strata are preserved) as a result of uplift of the Brabant Massif during the Cimmerian tectonic phase (Langenaeker, 2000). The north–south-trending Donderslag Fault Zone divides the Paleozoic basin into western and eastern parts that have contrasting sedimentological styles and different burial histories during deposition of the Coal Measures (Langenaeker, 2000).

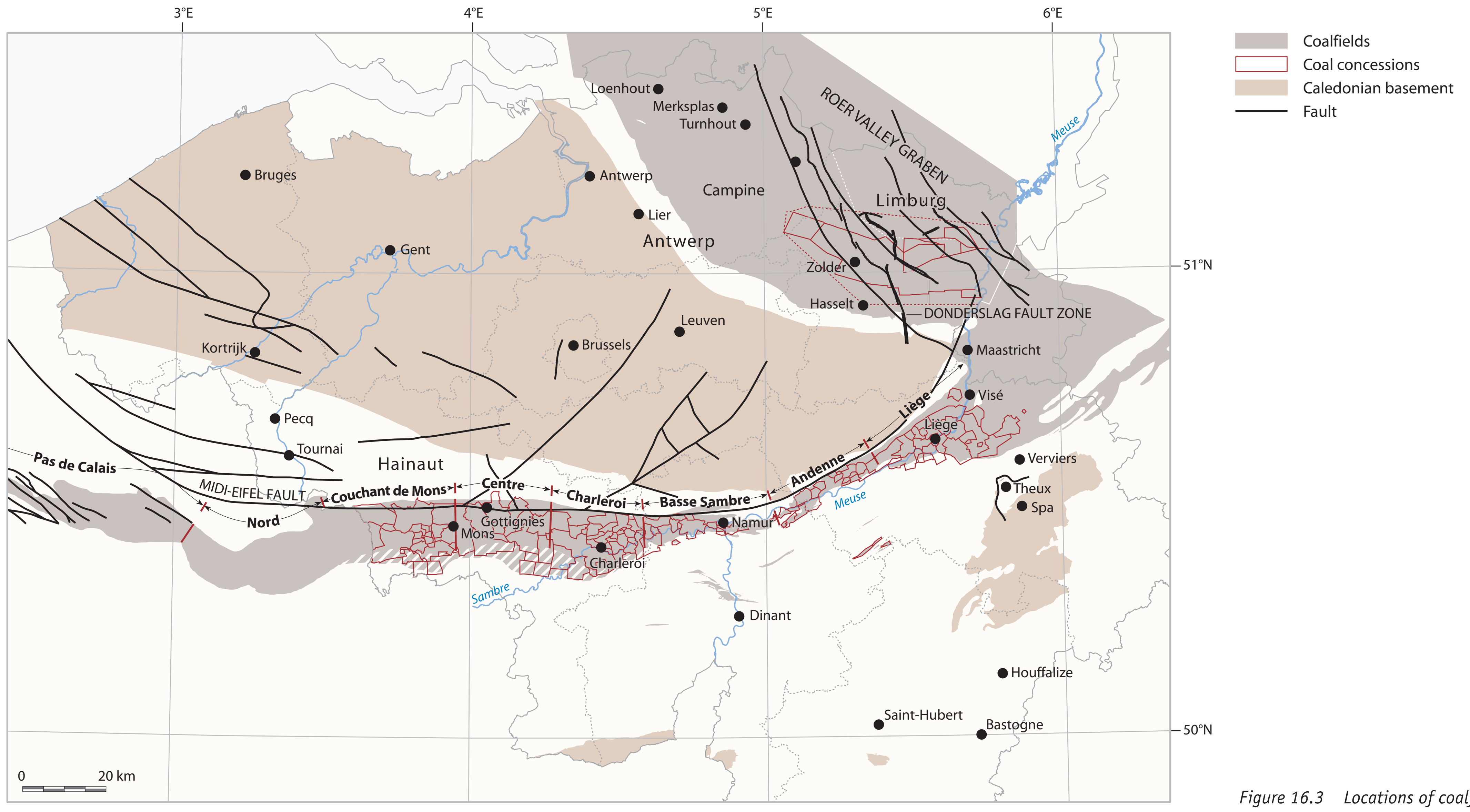


Figure 16.3 Locations of coalfields in Belgium.

Main characteristics, origin and type

The Upper Carboniferous coal deposits of Belgium are part of the north-west European paralic coal basin. The paralic coal swamps developed on top of delta systems and floodplains. The depositional facies gradually changed from lower delta-plain at the base to alluvial-fan during Westphalian D times. The oldest coal layers are Namurian, but the most productive levels are found in the Westphalian A to C sequence. The sequence is up to 3000 m thick and characterised by a cyclic alternation of mudstones and sandstones. It contains several coal layers that range from a few centimetres to 3 m thick; the average thickness of the mined layers in the Campine Basin is 1.35 m. The rank ranges from high-volatile bituminous coal to anthracite. The sulphur content is usually low (<2%); the ash content is variable.

Mining

More than 160 concessions have been granted in the Walloon Basin. Ten commercial concessions have been granted in Flanders, of which seven have been exploited. Apart from a few outcrops along the Sambre-Meuse axis and in the Theux Basin, the coal deposits are only accessible by underground mining. The deepest mines reach depths of about 1100 m. Longwall-mining methods were generally applied in all major collieries. The abandoned chambers could be back-filled, but in most cases were left to collapse, resulting in significant surface subsidence. Large amounts of groundwater are still pumped out to prevent flooding of the former mining areas (Minten et al., 1992).

Economic importance

The oldest indications of the use of coal date back to Roman times (near the Meuse River). In the 18th century, there was a boom in coal exploitation in the Walloon Basin, as the coal had both industrial and domestic use. At the beginning of the 19th century, the Borinage (Hainaut) was Europe's most important coal-mining area with production of approximately 2.25 million t/year (Gaier, 1988), which created the prosperity of the Sambre-Meuse axis area at that time. At the end of the 19th century, new exploration started in the north of the country (Minten et al., 1992). Production in the Campine Basin started in 1917 and steadily increased to a maximum of 10 million t/year in the 1950s and early 1960s (**Figure 16.4**). By that time, production in the Walloon coalfields was already in decline and finally ended by the mid-1980s. The closure of the Zolder colliery (**Figure 16.3**) in 1992 marked the end of production in the Campine Basin. Coal exploitation in both the Hainaut and Campine regions stopped due to high exploitation costs rather than by depletion of the coal reserves (**Table 16.1**). Belgian coal production reached its peak between the mid-1930s and mid-1950s and decreased during World War II (25-30 million t/year). In total, more than 2600 Mt of coal have been mined in Belgium.

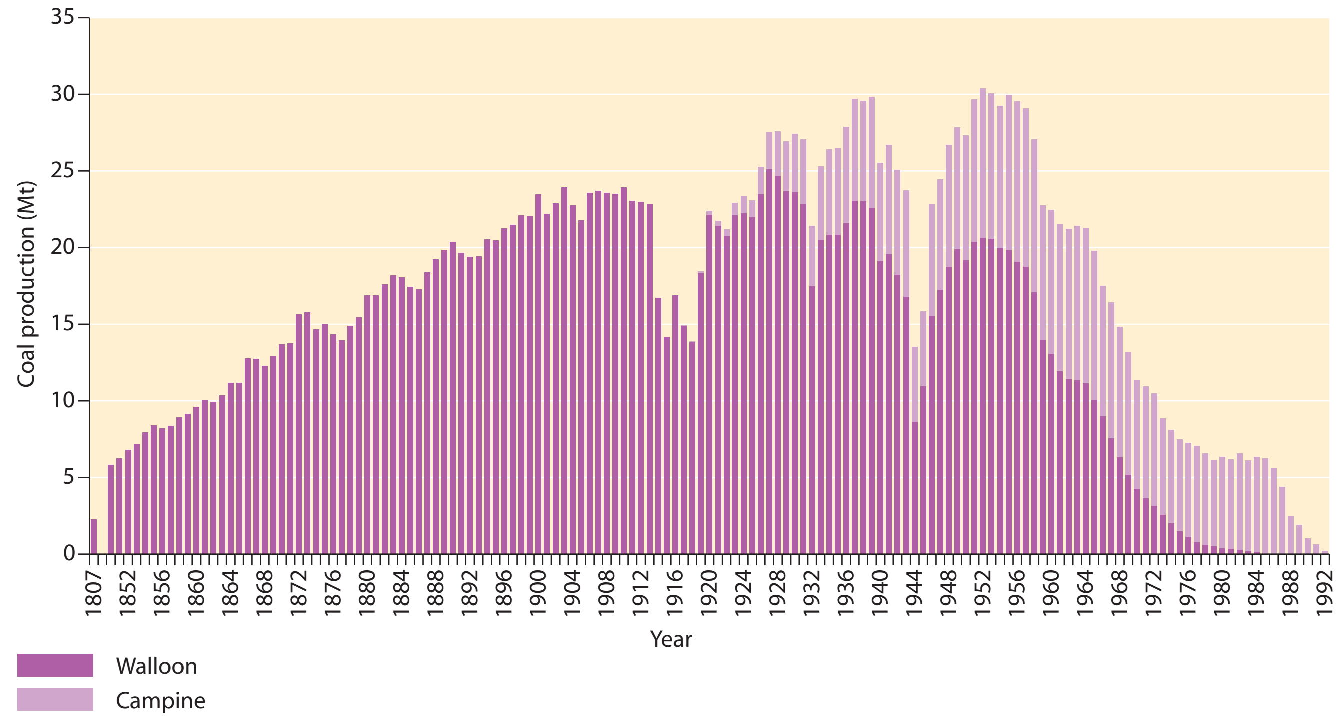


Figure 16.4 Annual production of coal in the Walloon and Campine basins of Belgium.

Table 16.1 Total coal production and estimated remaining resources in the Campine and Walloon basins.

	Area (km^2)	Total production (Mt)	Resources	
			Mineable (Mt)	Geological (Mt)
Walloon Basin	1680	2200	2 500	10 300
Campine Basin	3600	441	8 500	38 800
Belgium	5560	2641	11 000	49 100

Regulations and licensing

Since the State Reforms of 1982, natural resources have been regulated by the regions, who adopted new legislation to bring the old Mining Law of 15 September 1919 into line with the new constitution Décret des Mines - B.S. 27 Janvrier 1989 (err. 19.02.1991) of the Walloon region and Decreet houdende wijziging van de gecoördineerde mijnwetten B.S. 21 September 1982 (err. 28.01.1983) of the Flemish region. Brussels has declared the Mining Law of 1919 no longer applicable, but has not adopted a new regulation. Parts of the old Mining Law are still in force in the Flemish and Walloon regions. In addition to the Mining Law, regional regulations with respect to environmental impact, risk and waste apply to all mining activities.

2.3 The Netherlands

Location and geological settings

There are both coal and lignite deposits in the Netherlands (**Figure 16.5**). Bituminous to anthracitic coals are found in the Westphalian deposits that subcrop large parts of the country below the Base Permian Unconformity (Pagnier et al., 1987; Van Buggenum & Den Hartog Jager, 2007). Coal-bearing deposits are currently found at shallow depths in the southernmost Netherlands and deepen northwards to more than 3000 m beneath the surface. The main coal-bearing deposits occur in the Westphalian (A to C) Baarlo, Ruurlo and Maurits formations (see Chapter 6, **Figure 6.3**).

An important lignite field formed during Mid-Miocene times in the southern Netherlands (Limburg Province) in the so-called 'Hauptflöz' Group. The Heksenberg Member (up to more than 100 m thick) consists of unconsolidated sand and three to four lignite beds (Kuyl, 1973; Engelen, 1987). The beds may be more than 15 m thick (NITG, 1999). North of Sittard, lignite layers are 5 to 25 m thick at a depth of about 300 m (Van Rooijen, 1989). The lignite beds extend to the west and north-west into Belgium and Noord-Brabant, where the thickness decreases markedly. Farther east, remnants of these layers occur near the surface on a fault-bounded block.

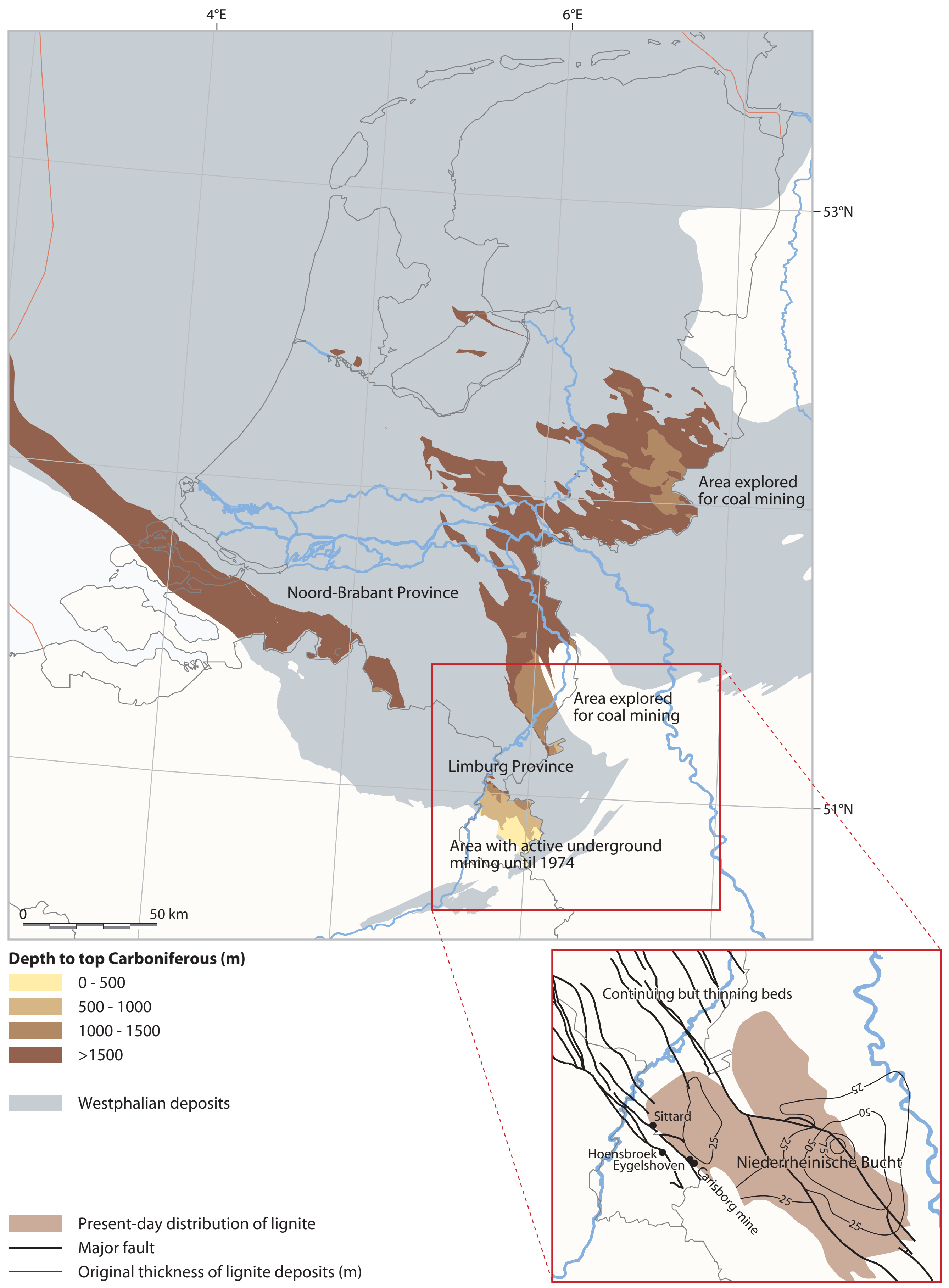


Figure 16.5 The distribution of Westphalian and lignite deposits in the Netherlands and surrounding areas. The depth to the top Carboniferous up to 1500 m is shown, which can be used to recognise possible areas for conventional mining in the Netherlands. The inset map shows detail of the present-day distribution and original thickness of lignite deposits in the southern Netherlands.

Main characteristics, origin and type
The coal-bearing Westphalian formations, which were originally up to 3000 m thick, were deposited in a cyclic river-dominated environment and have coal contents between 1 and 2.1% (Van Buggenum & Den Hartog Jager, 2007). The younger fluvial sandstones and shales of the Westphalian C and D locally contain thin coal seams (Van Adrichem Boogaert & Kouwe, 1993).

The Miocene lignites of the Limburg Province were deposited in the coastal zone of a Tertiary landmass and the so-called Niederrheinische Bucht, a fault-bordered subsiding area north-west of the German Eifel region (Van Rooijen, 1989) (**Figure 16.5**).

Mining
Mining of Westphalian coals started at the beginning of the 18th century, when the coal was extracted from small mine-shafts. Approximately 65 of the 248 seams are exploitable and they are about 50 to 150 cm thick (Kuyl, 1980). During the 19th century, coals were exploited by State-owned mines and private enterprises and the coal industry was fully established by the end of the century. Coal production intensified from the 1930s until after World War II when 12 surface facilities were in operation. Their combined annual production was as high as about 12.6 Mt (Engelen, 1989b). Production peaked in the early 1960s (Westen, 1971). Coal exploration also took place in the northern Limburg area and in the eastern Netherlands where a concession was granted, but for economic reasons the coals were not mined (Visser, 1987).

In the first half of the 20th century, local lignite exploitation took place in opencast mines, although the first concession had been applied for in 1858 in the town of Eygelshoven (Engelen, 1989a). Lignite exploitation gained importance during World War I, when several opencast mines started production near the towns of Eygelshoven and Hoensbroek. Most lignite mining came to an end in 1923 due to a drastic decrease in price, but attracted commercial interest again during and after World War II. Nearly 180 000 tons were mined in the quarries during 1943. Production from the Carisborg mine reached its peak in 1951 with extraction of 200 000 tons of lignite. In 1956, the total Dutch lignite production was around 300 000 tons; 100 000 tons of 'briket' (briquettes) were produced.

Economic importance
The collapse of bituminous to anthracitic coal mining in the Netherlands (Raedts, 1971; Van Tongeren, 1987) was the result of a combination of factors, including the discovery of the Groningen gasfield in 1959 (Van Tongeren, 1987), low world-energy prices, and rising exploitation costs. These led to rapid mine closures between 1967 and 1974. In the 20th century, approximately 570 Mt of coal were mined in the Netherlands (Westen, 1971). However, there are still enormous coal resources in Limburg and other areas (at depths shallower than 1500 m) estimated to be between 4000 and 38 000 Mt (Van Bergen et al., 2007). There was renewed interest in coal during the 1980s due to the oil crisis and to new techniques such as underground coal gasification, which led to an inventory of coal deposits down to a depth of 1500 m (Krans et al., 1986; Pagnier et al., 1987; Van Tongeren, 1987).

There was a steady decline in lignite production from the 1950s. Production ended completely in 1968 with closure of the Carisborg site due to exhaustion of the shallow-subsurface lignites and economics. The lignite resources in the Netherlands are calculated to be more than 1700 Mt (Van der Burgh et al., 1988). However, despite their relatively shallow depth, future exploitation is unlikely because of environmental concerns and the high population density in areas where the resource would be mined.

2.4 Denmark

Location and geological settings
Coal deposits in Denmark are limited in area (Petersen, 2004). Lower to Middle Jurassic coals are most widespread on Bornholm Island and the Øresund area (see **Figure 6.16**) and in the Danish sector of the North Sea (Petersen, 1993, 1994; Petersen & Nielsen, 1995; Petersen et al., 1998, 2003b). Lower Carboniferous coals have been encountered in a few wells in the Danish North Sea (Petersen & Nytoft, 2007b), whereas Miocene coals are found in Jylland in the Søby-Fasterholt area (Thomsen & Koch, 1989) (Chapter 12). Jurassic coals in the North Sea are well-documented from the Søgne Basin, where they occur in an overall transgressive setting and are ascribed to the Lulu Formation. Their formation on coastal plains was related to rises in relative sea level (Petersen & Andsbjerg, 1996). The Lower Jurassic coals of Øresund and Bornholm (Rønne and Sorthat formations) accumulated in freshwater mires situated farther inland. The Lower to Middle Jurassic coals on Bornholm accumulated in a pull-apart basin at the margin of the Fennoscandian Shield and are found in paralic coastal-plain and lacustrine successions. The Miocene coals in central Jylland were deposited in an overall deltaic setting.

Main characteristics, origin and type
Thin Lower Carboniferous coals are vitrinite-rich. Lower to Middle Jurassic coals formed in a humid, warm-temperate to subtropical, weakly seasonal climate. The Middle Jurassic coals in the Søgne Basin are mostly found at 3400 to 3800 m depth, but may be buried to about 5000 m towards the Tail End Graben. A total of nine coal seams have been identified; the thickest is about 2 m thick. The coals are vitrinite-rich (Petersen et al., 2003b). The Lower Jurassic coal seams are less than 0.6 m thick and the Middle Jurassic coals may be almost 2 m thick. The coals of the Bagå Formation on Bornholm are generally impure. The Miocene lignites have coal seams up to 2 m thick.

Economic importance
Denmark has no coal production and all coal is imported. The coals in the North Sea are of high volatile bituminous rank, whereas the coals onshore are of lignite to sub-bituminous rank. Until about 1970, the Miocene lignites in Jylland were mined by open-pit mining, but the generally high sulphur content, and the locally high ash content, rendered the coals unfavourable for mining. The import of coals of variable origin, composition and rank has promoted research into combustion properties of coals and combustion chars (Rosenberg et al., 1996; Sørensen et al., 2000). The current economic importance of coal is only as a source rock for oil and gas (Petersen, 2006; Petersen & Nytoft, 2006) (Chapters 12 and 13). In the North Sea, Lower Carboniferous coals may be a potential gas source, whereas Middle Jurassic coals have sourced the gas/condensate and oil produced in the Søgne Basin (Petersen et al., 1996, 1998, 2000; Petersen & Nytoft, 2007b).

2.5 Germany

Location and geological settings
There are three coal and four main lignite mining districts in Germany, all of which are in the western part of the country. The coals are Carboniferous in age (primarily Westphalian) whereas lignites are of Tertiary (Miocene) age. The most important coal-mining areas are the Ruhr and the Ibbenbüren districts (**Figure 16.6**), which have an area of approximately 5000 km^2. In these areas, the productive Namurian C to Westphalian D strata are up to 4200 m thick and contain up to 300 seams, although only about 160 seams are thicker than 0.3 m. The maximum cumulative coal thickness in the basin is approximately 135 m and the typical coal content ranges from 2 to 10%. The highest coal content is found mainly in the Bochum and Essen series (Westphalian A and B) (Drozdzewski, 1993; Füchtbauer, 1993; Juch et al., 1994; Dehmer, 2004). The most important lignite mining district is the Rhineland area (near Cologne), which has an area of more than 2500 km^2 (**Figure 16.6**).

The most productive succession is the lignite-bearing Miocene Ville Formation, which is up to 600 m thick and contains the main 100 m-thick seam (Hauptflöz). The Miocene to Eocene succession of the area between Brunswick and Leipzig (Helmstedt and Central-German mining district) has up to eight coal seams; the thickest that are currently mined range from 10 to 30 m. In the Lusatian mining district in eastern Germany, there are four Miocene seams, although coal is mined only from the 5 to 14 m-thick second seam, which covers an area of about 4000 km^2 (Luzin & Zheleznova, 1984; Pätz et al., 1989; Vulpius, 1993; DEBRIV, 2000, 2007a, 2007b).

Main characteristics, origin and type
The Carboniferous coals are humic and were deposited in a foredeep basin under paralic conditions. The coals are mainly low- to high-volatile bituminous rank with a low sulphur (<1%) and ash content (**Table 16.2**). Approximately 60% of the coal resources are steam coals (**Table 16.3**). Anthracite is only found in the Ibbenbüren and Aachen-Erkelenz mining districts and forms only a minor amount of the total coal resources. Most of the lignites are of paralic origin. The lignites have an average vitrinite reflectance of 0.3% and locally contain up to 3% sulphur (Helmstedt and Central-German mining districts) (**Table 16.2**) (Juch et al., 1994; Dehmer, 2004; BGR, 2007).

Table 16.2 Coal quality (BGR, 2007).

Type	Mining district	Heating value (MJ/kg)	Ash content (%)	Volatile components (%$_{waf}$)	Total sulphur content (%$_{wf}$)	Moisture (%$_{wf}$)
Coal	Ruhr	28-33	5-10	8-45	0.5-4	-
Coal	Ibbenbüren	32.5	3-4	5-6	0.6-0.9	-
Lignite	Rhineland	7.8-10.5	1.5-8	-	0.1-0.5	50-60
Lignite	Helmstedt	8.5-11.5	5-20	-	1.5-2.8	49-53
Lignite	Central-German	9-11.3	6.5-8.5	-	1.5-2.1	40-50
Lignite	Lusatian	7.6-9.3	2.5-16	-	0.3-1.5	48-58

Table 16.3 Production, reserves and estimated resources of solid-fuel minerals (Juch et. al., 1994; BGR, 2007).

Type	Mining district	Production (2006) (Mt)	Reserves (Mt)	Resources (Mt)
Coal	Ruhr	15.133	101.8[1]	46 898
Coal	Ibbenbüren	1.912	12.8[1]	14 487[2]
Coal	Aachen-Erkelenz	closed in 1997	0	6 500
Lignite	Rhineland	96.178	35 000	20 000
Lignite	Helmstedt	1.804	18	360
Lignite	Central-German	20.353	2 100	7 900
Lignite	Lusatian	57.955	3 700	8 500

1 Producible amount (subsidised) until 2018.
2 Includes resources in the Münsterland area.

Mining
Coals are exploited by longwall-mining methods from usually 1 to 2 m-thick seams in seven underground mines at depths of 1000 to 1600 m (SdK, 2007). Lignite from seams between 5 and 70 m thick are extracted in large surface mines. Lignites are mined in the Rhineland district at depths of 40 to 350 m (locally up to 550 m at Hambach) and in the Central-German and Lusatian districts at depths of 80 to 120 m. On average, the extraction of 1 tonne of lignite requires the removal of 5.3 m^3 of overburden, which has a significant environmental impact. Up to 2007, about 66% of the former lignite-mining areas in Germany were recultivated (DEBRIV, 2007a, 2007b).

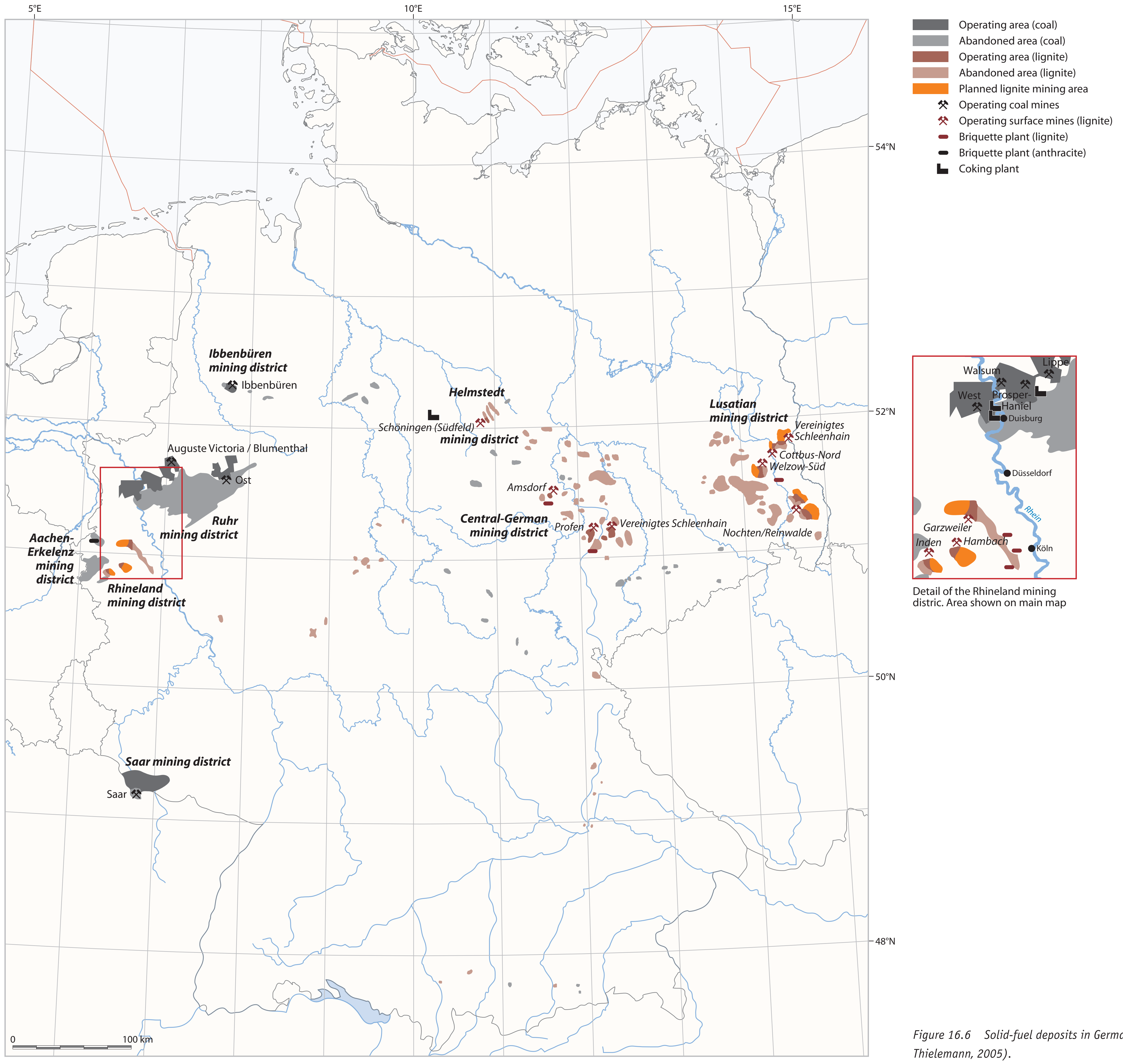


Figure 16.6 Solid-fuel deposits in Germany (modified after Thielemann, 2005).

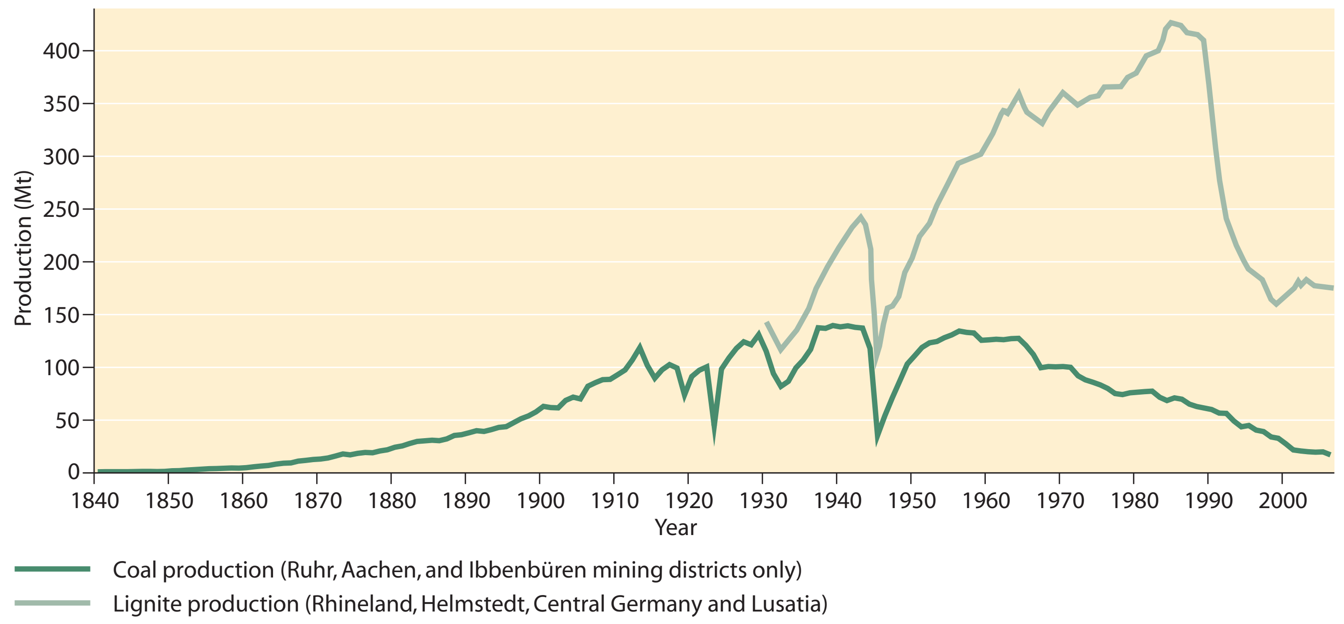


Figure 16.7 Development of German coal and lignite production.

Economic importance

In 2006, the primary energy demand in Germany was supplied by oil (35.7%), natural gas (22.8%), coal (13%) nuclear power (12.6%), lignite (10.9%) and renewable energy sources (5.5%). Coal is the major indigenous energy resource. In 2006, all lignite and about 34% of coal demand were provided by domestic production. After World War II, there was a continuous reduction in coal mining from 153 Mt in 1956 to around 21 Mt in 2006 (**Figure 16.7**). In 2006, total imports of coal and its products rose to 46.5 Mt (66% of consumption). The remaining coal came from eight highly subsidised domestic coal mines. The seven coal mines of the Ruhr and Ibbenbüren mining districts produced 17 Mt, which is 82.4% of the total German coal production. Coal production will be reduced to 12 Mt in 2012 and subsidised coal production will probably end in 2018.

Germany is by far the most important lignite producer in the world (**Figure 16.7**) with 176.3 Mt in 2006 (BGR, 2007). About 92% of the total German lignite production is moved directly to pit-mouth power plants for electricity generation (163 Mt in 2006). The most productive are the Rhineland, Lusatian and Central-German mining districts (**Table 16.3**). In addition, about 300 mln m^3 of methane emitted from abandoned coal mines was used in more than 120 small combined power and heat plants in the Ruhr mining district during 2006 (Ministerium für Wirtschaft Mittelstand und Energie des Landes Nordrhein-Westfalen, 2007).

Regulations and licensing

The Mining Law regulates lignite and coal mining, the ownership of lignite and coal deposits, as well as mining activity, mine-closure procedures and environmental impact assessments.

2.6 Poland

Location and geological settings

Most of the Paleogene to Neogene lignite deposits are found in western and central Poland (**Table 16.4**, **Figure 16.8**). A few small low-rank coal deposits occur in the Kraków-Wieluń Upland (Liassic) and the Carpathian foredeep (Neogene) (Ciuk & Piwocki, 1990). Lower and Middle Miocene coal seams are economically significant in the Polish Lowlands where they extend over an area of about 70 000 km^2 and continue into the Lower Lusatian lignite basin of eastern Germany. The lignites occur mainly in tectonic depressions and are concentrated in eight major economic regions (Kasiński et al., 1991) where ten coal seams have been identified. The three oldest seams (from Upper Paleocene to Lower Miocene) are no longer economic. In south-west Poland, the Lower Miocene lignite seams include the 4th Dąbrowa seam, which covers an area of about 7000 km^2 and is up to 30 m thick (average 5.8 m) and the 3rd seam (Ścinawa), which has an area of about 30 000 km^2 and thickness up to 35 m (Piwocki, 1998a). The main coal-bearing horizon is formed by the two youngest Lower to Middle Miocene seams. The 2nd Lusatian seam has an area of about 61 000 km^2, is usually up to 40 m thick, and is locally up to 250 m thick (e.g. the Bełchatów deposit of the Kleszczów Trough; **Figure 16.8**) (Piwocki, 1992). The 1st Mid-Polish lignite seam is up to 20 m thick and has an area of about 70 000 km^2.

Main characteristics, origin and type

The Lower Jurassic and Upper Cretaceous coals are sub-bituminous and metalignites; hypolignites occur within the Paleogene-Neogene deposits. The Miocene coals of the four economic seams are hypolignites. The best quality lignites are from the Wielkopolska Region, characterised by high heating value, low ash content and quite low sulphur content. Lignite from the Western Region contains a little more sulphur; the poorest quality lignites are found in the Radom Region. The 2nd coal seam has the best quality, mainly because of the relatively low sulphur content (**Table 16.5** & **Figure 16.9**); however, the coal parameters change within the deposits, particularly in tectonic depressions. Tertiary lignites of the Polish Lowlands developed in the proximal-peripheral part of the Tertiary North-west European Basin (Vinken, 1988) during transgressive-regressive cycles (Kasiński, 2005). Their origin is related to regional epeirogenic subsidence of structural elements that generated lows (Kasiński, 2004) in which phytogenic material accumulated in brackish conditions (Piwocki et al., 2004a). Some thick coal seams also developed above salt diapirs where dissolution created accommodation space. The Elsterian and Saalian glaciations removed part of the shallow-buried coal seams.

Mining

In the 19th and 20th centuries, lignite was mined from small underground mines, but today it is extracted from opencast mines. New excavation technologies may be considered in the near future, such as a prototype installation for underground lignite gasification and microbial hydrocarbon synthesis. Opencast lignite mining causes locally significant environmental impacts such as long-term transformation of the soil surface; transformation of water conditions by dewatering of mines; secondary surface geomechanical deformation; earth tremors; contamination of surface and underground water; air contamination and noise.

Table 16.4 Major lignite resources in Poland (deposits of more than 100 million Mg).

No.	Deposit	Status	Area (km^2)	Economic resources (mln Mg)	Over-burden ratio	Chemical/physical parameters: Heat value Q^r_i (%)	Ash content A^d (%)	Total sulphur content S^d_t(%)
1	Babina-Żarki	abandoned	12.00	142.16	9.8	9 332	18.28	1.10
2	Bełchatów	mined	15.10	571.6[1]	2.6	9 018	20.97	1.28
3	Cybinka	unexploited	20.21	348.65	9.1	9 407	17.40	1.28
4	Cybinka Wschód	unexploited	10.98	178.68	9.1	9 596	15.12	1.94
5	Cykowo-Sepno-Racot	unexploited	7.20	110.59	11.6	9 704	16.23	1.08
6	Czempiń	unexploited	25.70	1 034.58	7.6	9 475	16.55	1.10
7	Dęby-Izbica	unexploited	11.12	112.62	9.6	8 337	25.19	1.46
8	Dobrosułów	unexploited	7.62	190.68	9.0	9 311	18.10	1.84
9	Gostyń	unexploited	49.20	1 988.83	6.3	8 864	20.62	1.24
10	Góra	unexploited	27.50	818.40	7.9	9 755	14.50	0.72
11	Górzyca	unexploited	43.66	369.71	11.2	7 147	33.78	1.32
12	Gubin	unexploited	22.90	282.66	6.7	9 257	15.62	1.64
13	Gubin-Brody	unexploited	109.74	1 934.34	7.2	9 536	16.62	2.66
14	Kamieńsk	unexploited	7.90	132.42	9.2	8 140	25.81	1.02
15	Krzywiń	unexploited	18.10	665.51	7.1	9 383	14.89	0.70
16	Legnica Północ	unexploited	38.51	1 465.41	8.1	9 106	19.02	1.56
17	Legnica Wschód	unexploited	38.14	839.31	7.6	8 877	20.89	1.36
18	Legnica Zachód	unexploited	37.33	863.64	6.6	9 769	15.87	0.86
19	Lubstów	mined	11.99	14.09[2]	4.1	9 499	19.43	1.00
20	Mosina	unexploited	39.14	1 580.54	5.8	9 206	18.61	0.62
21	Mosty	unexploited	20.50	220.00	8.0	9 387	18.10	1.56
22	Mosty NE	unexploited	17.48	332.62	11.7	9 096	19.28	1.80
23	Nakło	unexploited	11.70	255.00	6.6	7 976	24.22	1.22
24	Oborniki	unexploited	22.48	206.30	7.4	8 938	22.13	1.32
25	Osięciny-Kąkowa Wola	unexploited	19.10	132.94	11.5			
26	Piaski	unexploited	16.52	114.48	7.3	8 716	24.80	1.44
27	Pogorzela	unexploited	4.00	142.56	6.8	9 606	16.82	1.68
28	Poniec-Krobia	unexploited	97.86	1 749.74	9.2	9 190	18.77	0.60
29	Radomierzyce	unexploited	22.32	180.00	4.3	7 880	31.61	1.30
30	Rogóźno	unexploited	15.30	772.76	4.3	9 555	16.29	3.62
31	Ruja	unexploited	18.04	331.93	8.4	9 496	17.27	0.60
32	Rzepin	unexploited	20.36	249.53	7.9	9 060	15.14	1.20
33	Sądów	unexploited	14.82	226.47	10.2	9 165	18.80	1.38
34	Szczerców	mined	12.00	876.70	2.3	7 746	24.10	2.52
35	Sieniawa	mined	10.55	150.68	2.5	8 470	20.37	1.56
36	Sulechów-Świebodzin	unexploited	21.55	315.09	9.7	9 006	21.09	2.24
37	Szamotuły	unexploited	32.00	829.44	7.2	10 161	12.00	0.40
38	Ścinawa	unexploited	44.60	1 568.56	9.1	9 996	11.20	0.54
39	Ścinawa-Głogów	unexploited	268.02	8 970.70	7.6	8 439	13.25	2.58
40	Torzym	unexploited	39.27	843.88	7.9	9 504	16.80	1.80
41	Trzcianka	unexploited	91.61	300.08	9.0	8 663	19.46	1.80
42	Turów	mined	54.00	914.12[1]	1.8	9 133	21.80	0.98
43	Wieruszów	unexploited	12.00	117.60	9.1	8 367	26.23	0.72
44	Więcbork	unexploited	13.56	354.76	9.0	7 722	29.06	0.96
45	Złoczew	unexploited	8.75	485.62	4.5	8 462	21.67	1.18

1 Primary resources more than 1 billion Mg. 2 Primary resources more than 100 million Mg.

Economic importance

Lignite is one of the most important energy sources in Poland. Coal provides almost the entire energy source for heating in five pit-mouth power plants, which generate about 52 million MW-h (megawatt hours) per year and contribute about 40% of Poland's heating requirements. Lignite is also used for briquettes (13%) and tar production (21%) (**Table 16.6**).

The present economic resources and reserves of Neogene lignite in Poland are 15 936.46 Mt (according to data from December 2005), with reconnaissance resources (according to the United Nations Framework Classification of Resources/Reserves of Solid Fuels and Mineral Commodities) of 38 218.15 Mt. The total economic resource (as defined above) of the operating mines is 2014.43 Mt, of which 1661.46 Mt have been proven. The lignite resources in tectonic/halotectonic depressions are much greater then those on platform areas. Known lignite resources cover an area of about 5400 km^2, of which prospected and explored deposits have an area of about 900 km^2. The total area of exploited deposits is estimated to be 100 km^2.

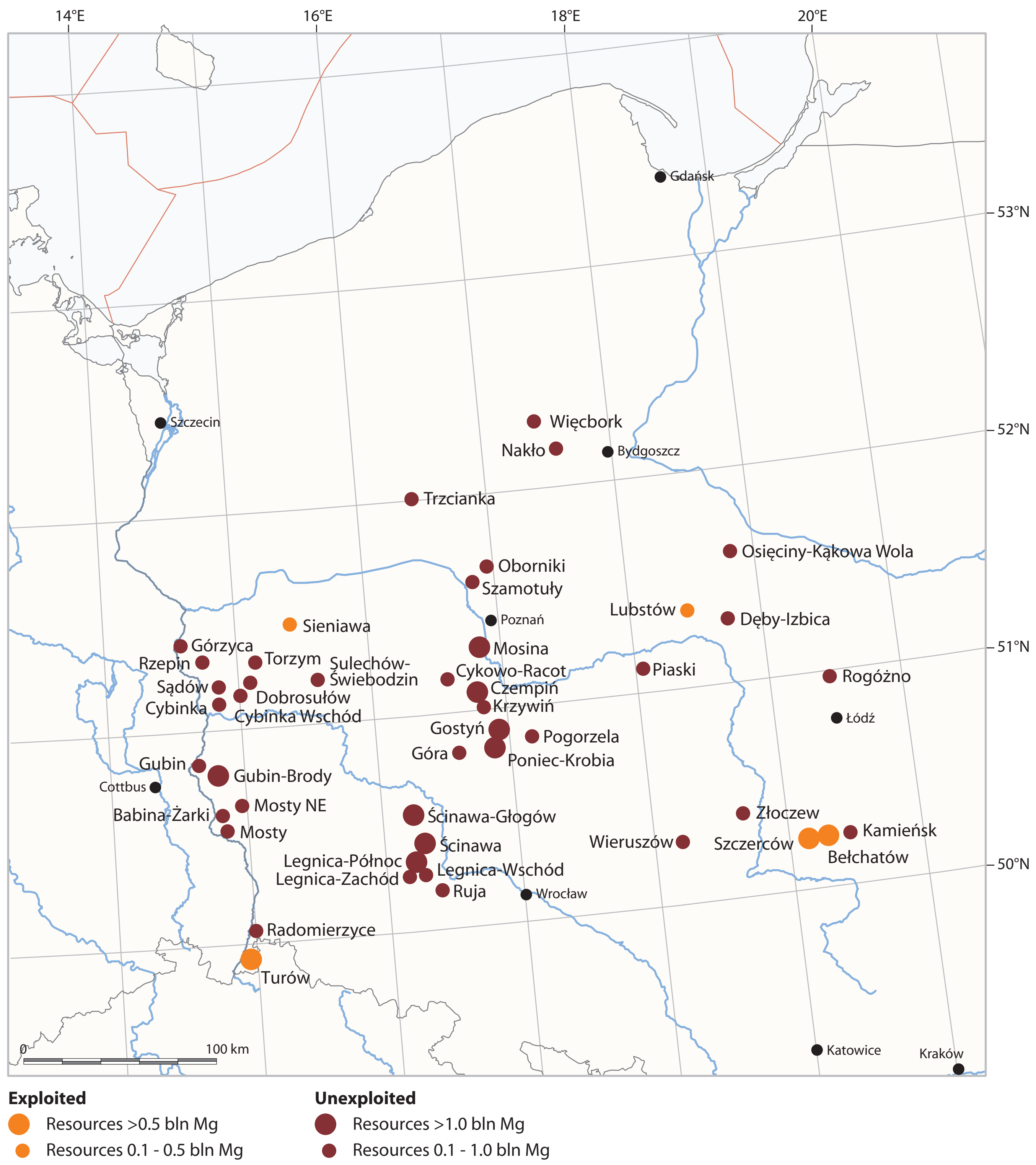


Figure 16.8 Major lignite resources in Poland. Detailed information from each field is given in Table 16.4.

Lignites of the 2nd and 1st coal seams provide most of the lignite resources and reserves in Poland; lignites of the 2nd seam represent about 65%, and those of the 1st seam about 25% of the total resources. The eight major lignite regions of western and central Poland have more than 40 Mt of coal. The largest resources are Miocene low-rank coals with good geological/mining parameters, which are mined today in five opencast mines. The largest (Adamów, Bełchatów, Konin, and Turów) produce about 60 Mt of lignite per year.

Regulations and licensing

Lignite mining in Poland is regulated by The Geological and Mining Law, which covers ownership of the deposits, mining activity and mine-closure procedures. Part of the mining activity is regulated by the Water Law (water conditions) and the Waste Law (mining wastes). The Minister for the Environment is responsible for licensing both lignite prospectivity and lignite mining.

Table 16.5 Average chemical/physical parameters of the coal seams (after Kasiński & Piwocki, 2002).

Parameter	Symbol	Unit	Coal seam 1st	2nd	3rd	4th
Volatile component	V^{daf}	%	56.12	53.49	54.28	56.08
Elementary carbon	C^{daf}	%	61.36	65.39	66.79	65.84
Elementary hydrogen	H^{daf}	%	4.97	4.82	4.65	5.20
Heating value	Qri	MJ/Mg	7976.00	8989.00	9169.00	9613.00
Ash content	A^d	%	27.53	20.73	21.09	17.85
Total sulphur content	S^d_t	%	1.25	1.31	2.40	2.91
Tar output	T^d_{sk}	%	10.53	10.94	9.50	12.00
Bitumen content	B^d	%	4.47	4.45	4.00	5.00
Moisture	W^r_i	%	52.50	52.80	51.00	50.00

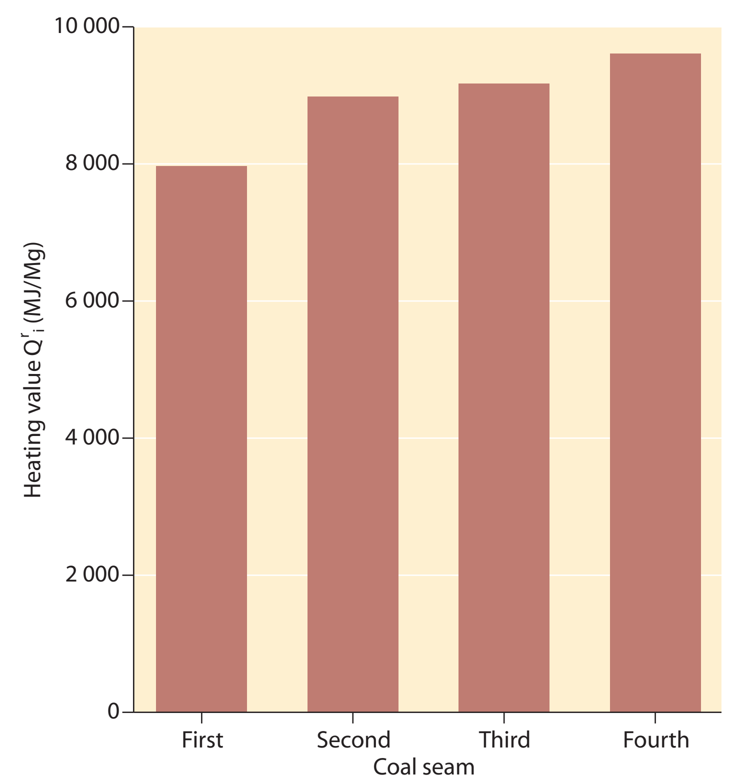


Figure 16.9 Distribution of basic coal-quality parameters within the major lignite seams.

Table 16.6 Basic average parameters of lignite exploited in Polish mines.

Parameter	Symbol	Unit	Value
Heating value	Q^r_i	MJ/Mg	8 000 - 9 300
Ash content	A^d	%	18-27
Total sulphur content	S^d_t	%	1.6
Bitumen content	B^d	%	4.4
Tar output	T^d_{sk}	%	11.5
Alkali content	$(Na_2O+K_2O)^d$	%	0.17
Moisture	W^r_t	%	53

3 Geothermal energy

3.1 United Kingdom

Tectonic units and geothermal regime

The amplitude of the background heat-flow field in the UK is thought to be about 52 mW/m^2, although there is considerable local variation from this value at the western margin of the SPB. Most of the variation probably results from local convective groundwater flow (Andrew-Speed et al., 1984; Rollin et al., 1998), but two areas of significantly higher heat flow have some relationship with the structure and lithology of the underlying Carboniferous and Lower Paleozoic rocks. For example, the area of significantly higher (locally >70 mW/m^2) than average heat flow to the north-north-east of Nottingham (**Figure 16.10**) has been attributed to regional eastward movement of groundwater following the dip of Carboniferous rocks from their outcrop in the Pennines towards the SPB area and locally ascending via a buried Carboniferous high into the overlying Permian and Mesozoic rocks (Bullard & Niblett, 1951; Downing & Howitt, 1969). The area of higher than average heat flow (locally >90 mW/m^2) to the south-west of Newcastle-upon-Tyne (**Figure 16.10**) is more directly structurally related, resulting from radioactive heat generation in the buried Early Devonian Weardale Granite intruded into Lower Paleozoic rocks that form the basement of a Carboniferous high (Alston Block). This granite has been identified as a potential hot dry rock geothermal target (Lee, 1986; Manning et al., 2007), but is presently undeveloped. Other Caledonian granites at the western margin of the SPB do not generate high heat-flow anomalies. The onshore UK part of the basin is therefore characterised by low-enthalpy geothermal resources with temperatures greater than 40°C, resulting from down-dip migration of groundwater from the margin into deeper parts of the SPB (Gale & Holliday, 1985; Downing & Gray, 1986; Rollin et al., 1998). Potential heat sources at depth have been evaluated in rocks of a wide range of lithologies and ages, with Permo-Triassic sandstones thought to provide the best prospect.

Geothermal systems

Two principal regional aquifers in eastern England have been identified with potentially significant quantities of hot brine (60°C+) to low-enthalpy two-borehole 'doublet' systems from depths in the range of 1500 to 2000 m (Gale & Holliday, 1985; Smith, 1987). The Triassic Sherwood Sandstone Group is by far the more important of these aquifers (**Figures 16.11** & **16.12**) and contains the largest store of low-enthalpy geothermal energy, but at relatively low temperatures (40-55°C). The rocks commonly retain good porosity and permeability at depth (<25% and <1000 mD respectively) and locally exceed 500 m in thickness.

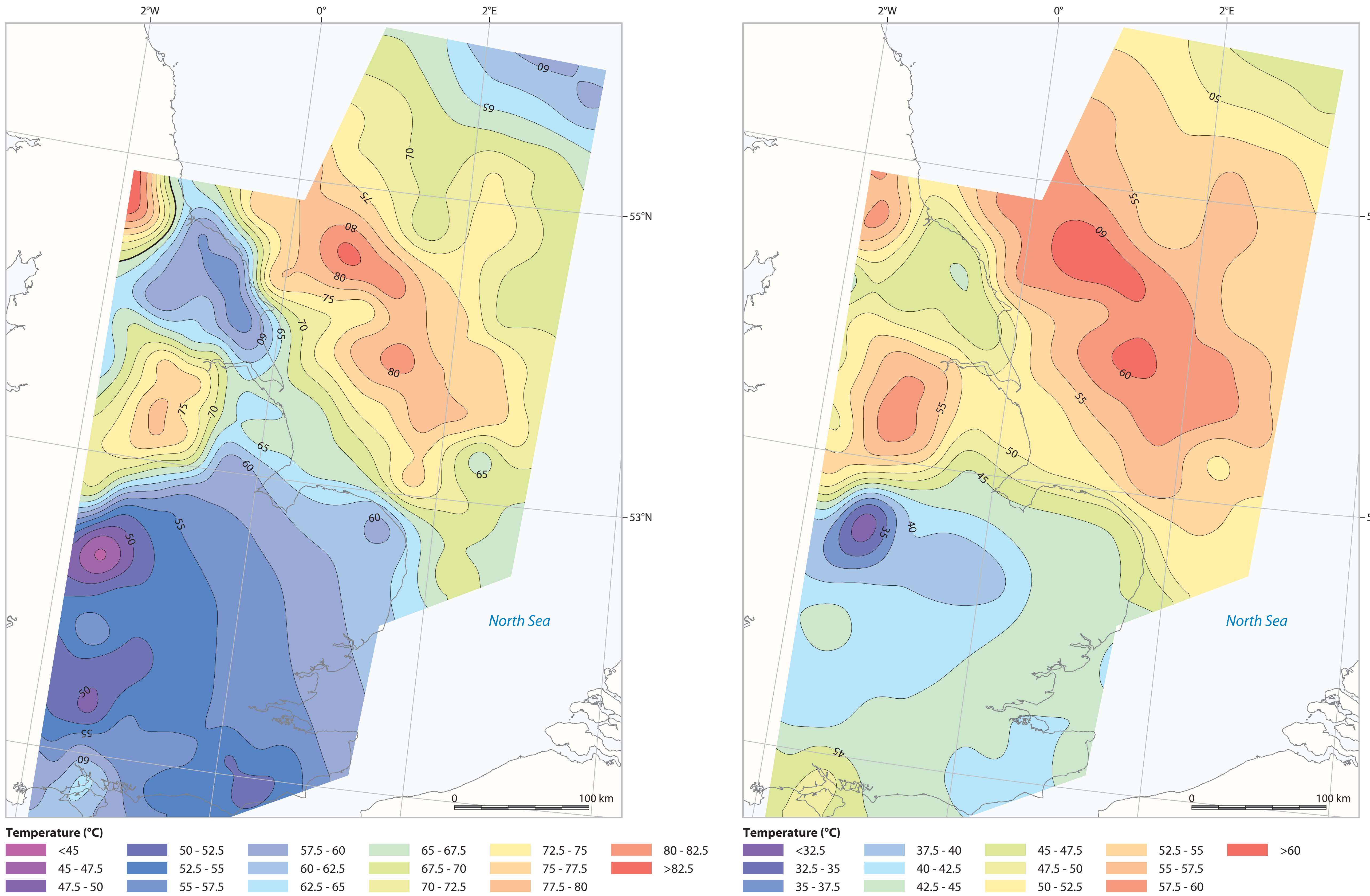


Figure 16.10 a. Heat-flow data for the UK onshore and offshore areas; and b. computed temperature at 1000 m depth. From vertical conductive transfer model based on heat flow. The areas shown in each map are where there is confidence in the data quality.

Temperatures in the middle of the aquifer are estimated to exceed 60°C only locally. Temperatures in the Permian Yellow Sands Formation locally exceed 70°C in coastal areas, with some attractive porosity and permeability values from some borehole cores, typically about 25% and <650 mD respectively; however, the formation is less than 30 m thick.

Economic importance

Downing & Gray (1986) estimated the geothermal heat in place (H_0), and the total identified resource (H_1) for the Triassic Sherwood Sandstone Group in eastern England, where aquifer temperatures are more than 40°C, at 99×10^{18} J and 10.6×10^{18} J respectively. In a more recent study, Rollin et al. (1998) made somewhat larger estimates ($H_0 = 122 \times 10^{18}$ J; $H_1 = 20 \times 10^{18}$ J). The geothermal potential of the Yellow Sands Formation, $H_0 = 5.4 \times 10^{18}$ J and $H_1 = 1.02 \times 10^{18}$ J (Downing & Gray, 1986) is not considered to be attractive at the present time. No exploitation has occurred in the area, apart from limited application of ground-source heat pump technology and shallow, low-temperature, groundwater sources.

Regulations and licensing

The statutory body in the UK with responsibility for managing the extraction and discharge of geothermal waters is the Environment Agency. If water is to be extracted from an underground source, such as a well or borehole, a groundwater consent to construct is needed and a pumping test must be carried out before an application for an abstraction licence is considered. Appropriate abstraction and discharge licences have to be issued by the Agency before a geothermal prospect utilising geothermal waters could be developed, to protect both water supplies and the environment (current regulations are available at www.environment-agency.gov.uk).

3.2 Belgium

Tectonic units and geothermal regime

The geothermal potential of Belgium is found mainly in the sedimentary basins north and south of the Caledonian Brabant Massif (Campine and Hainaut basins). Both areas are characterised by strong subsidence during much of their Late Paleozoic to Recent history, which has resulted in the deposition and preservation of thick sedimentary units. In the Campine Basin, widespread extensional faulting is related to the development of the Roerdal Graben; heat fluxes are higher along its bounding faults.

Geothermal systems and their economic importance

The geology of Belgium is only suitable for production of low-enthalpy geothermal energy from several deep aquifers in the areas north and south of the Brabant Massif (**Figure 16.13** & **Table 16.7**). The most important geothermal reservoir in Belgium is the Carboniferous Limestone Group (Haenel & Staroste, 1988). In the Campine Basin, the best reservoir levels are related to palaeokarst horizons. Formation water reaches a temperature of 100°C at approximately 2500 m (at Turnhout and Merksplas; see **Figure 16.13**). In the north-east Campine Basin, other potential geothermal reservoirs are related to sandstones of the Buntsandstein Group, which are approximately 200 m thick with an effective porosity of 12% and average permeability of 35 mD, and the Neeroeteren Formation, which is up to 300 m thick and has an average

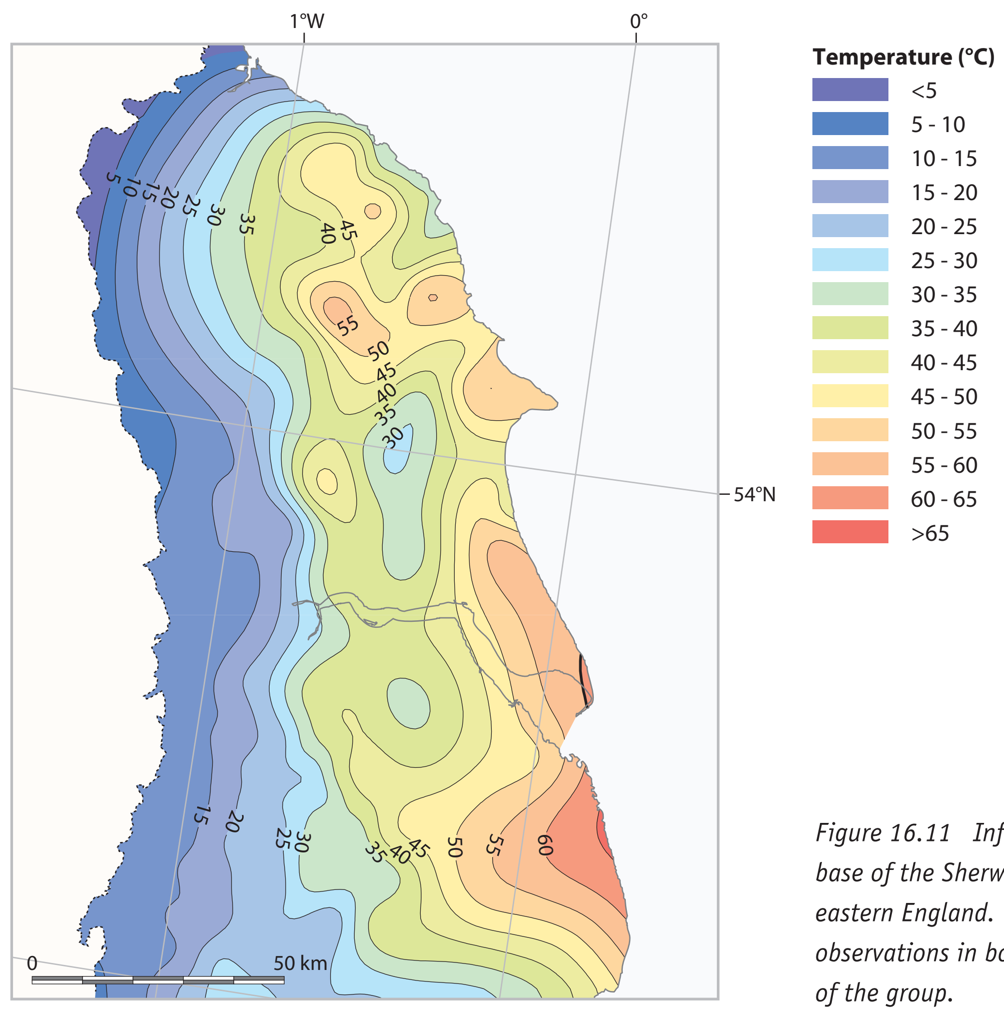


Figure 16.11 Inferred temperatures at the base of the Sherwood Sandstone Group in eastern England. Data are from temperature observations in boreholes penetrating the base of the group.

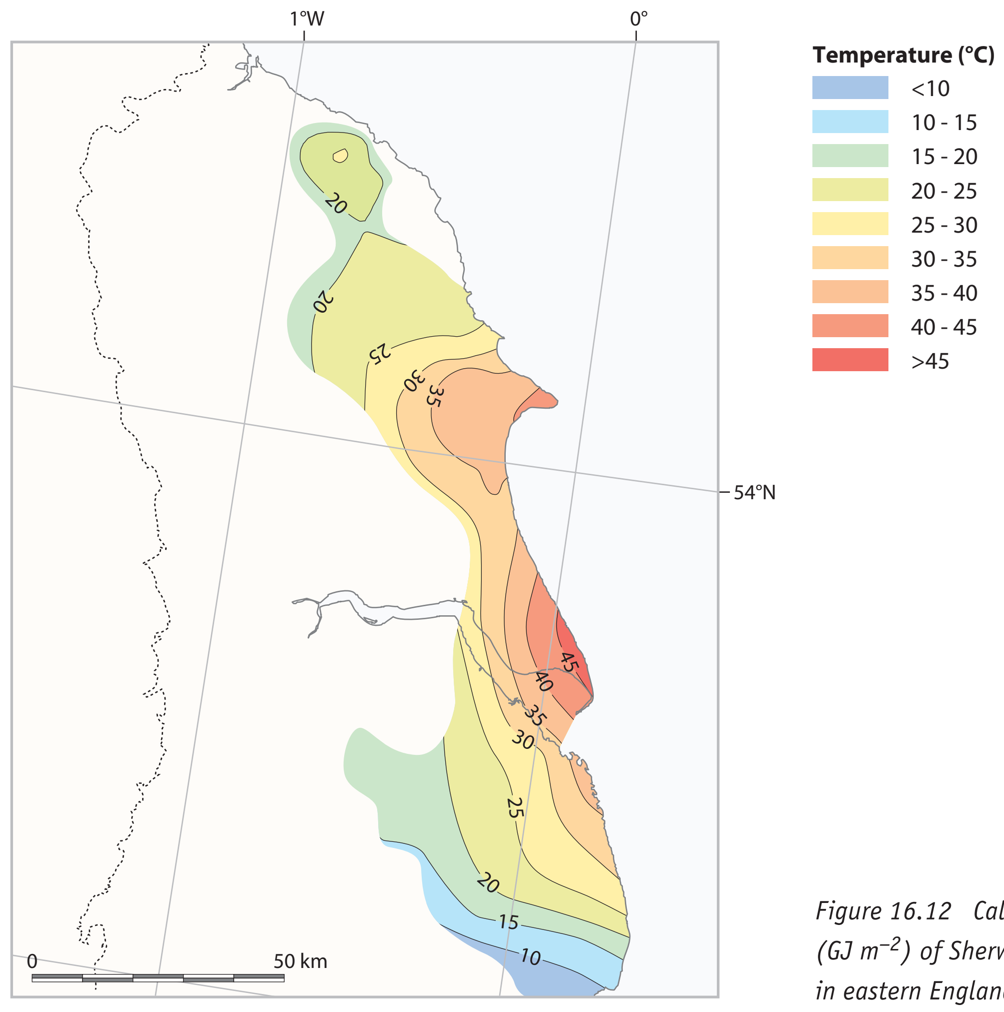


Figure 16.12 Calculated geothermal resources (GJ m^{-2}) of Sherwood Sandstone Group strata in eastern England.

porosity of 15% and permeability of 110 mD (Laenen et al., 2004). In the northern part of the Campine Basin, porous chalk arenites at the top of the Cretaceous are up to 80 m thick with porosities up to 30% and average permeability of the order of 50 mD. These arenites also have limited geothermal potential, but recorded temperatures are low (<45°C) (Berckmans & Vandenberghe, 1998). In the Campine Basin, water from the Upper Cretaceous chalk is used to heat swimming pools at Herentals and Turnhout and to heat the water of a fish farm at Dessel. The annual energy use at these three sites is 12.5 TJ. South of the Brabant Massif, the main geothermal reservoir is formed by the dissolution of the Carboniferous Limestone Group evaporites and the associated collapse of the overlying strata. In the Hainaut Province, the Carboniferous aquifer is currently exploited by two deep wells at Saint-Ghislain and Douvrain (**Figure 16.13**). The Saint-Ghislain aquifer has an artesian flow rate of 100 m^3/h and a production rate of 60 m^3/h. The temperature of the produced water is 73°C and the salinity of the formation water less than 2 g/l. The water is used for heating or air conditioning in homes, greenhouses, sports facilities and a hospital and school; the remaining heat is used to produce bio-gas from waste sludge. The total annual energy use is 79.5 TJ (Berckmans & Vandenberghe, 1998). At Douvrain, the produced water has a

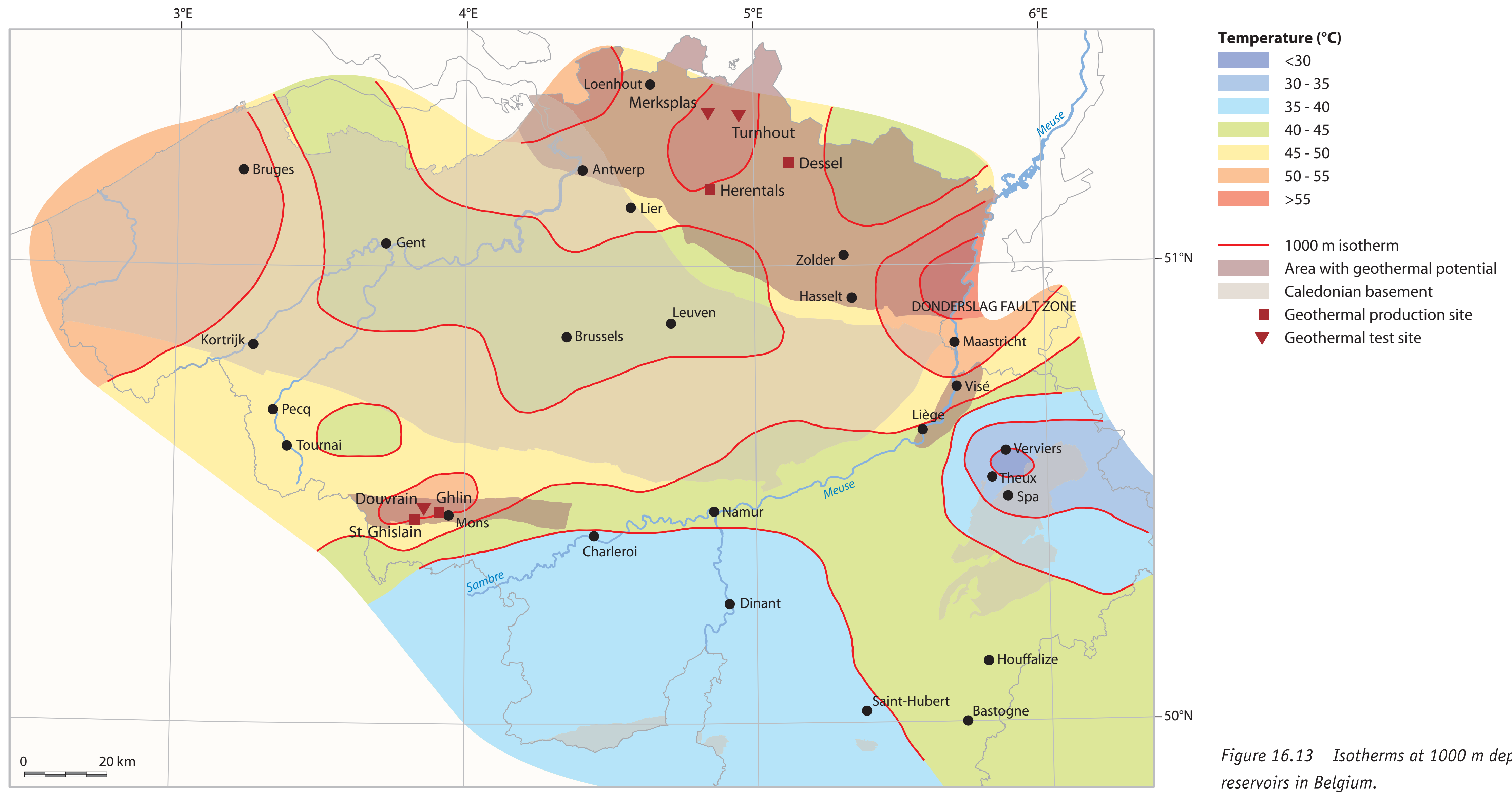


Figure 16.13 Isotherms at 1000 m depth and location of potential low-enthalpy reservoirs in Belgium.

temperature of approximately 65°C, the average flow rate is 10.5 m^3/h and annual energy use amounts to 9.59 TJ. Finally, in the vicinity of Liège (east of the Brabant Massif), karstified Devonian and Carboniferous carbonates have only limited geothermal potential. The reservoir is at a shallow level and so temperatures are consequently low.

Regulations and licensing

Extraction of geothermal energy is regulated by the Energy Departments of the Flemish, Walloon and Brussels regions. The regulations differ in each region. Compliance with regional safety and environmental regulations is also required for exploitation of geothermal wells.

Table 16.7 Direct use of geothermal energy in Belgium (data from Berckmans & Vanderberghe, 1998).

Aquifer	Area (km^2)	Potential (GJ)	Dissolved solids (g/l)
Cretaceous – Campine	2155	17.7×10^8	3-30
Buntsandstein – Campine	530	50.8×10^8	-
Neeroeteren – Campine	52	1.23×10^8	5-15
Carboniferous Limestone Group – Hainaut	373	29.0×10^8	1-2
Carboniferous Limestone Group – Campine	2096	44.5×10^8	135-300
Devonian/Carboniferous – Liége	113	18.5×10^8	-

3.3 The Netherlands

Tectonic units and geothermal regime

The subsurface of the Netherlands is regarded as being part of a low-to-moderate enthalpy basal heat-flow regime. Apart from local thermal anomalies related to high-conductivity evaporites or presumed local upward fluid flow along faults, the temperature data within the first 3000 m are indicative of a relatively uniform heat flow of around 60 to 65 mW/m^2, characteristic of Phanerozoic continental lithosphere. Several rifting and inversion stages, including ongoing neotectonic graben formation in the Roer Valley Basin, have affected the thermal structure of the lithosphere underlying the Netherlands. Basin-analysis and lithosphere-rifting models show that the undifferentiated heat flow observed in sedimentary infill of the (neotectonic) basin margins towards the basin centres are consistent with passive rifting in which extensional thermal attenuation in the deeper crust is counterbalanced by cooling of the sediment infill (e.g. Van Balen et al., 2000; Van Wees et al., 2008; Luijendijk et al., 2009). The models are consistent with a deep-lithosphere thermal structure derived from seismic tomography, demonstrating that the Netherlands are not underlain by deep-seated thermal anomalies in excess of the thermal effects predicted by passive rifting (e.g. Goes, 2000).

Geothermal systems

Aquifers of sufficient thickness and relatively high permeability and temperature suitable for the extraction of geothermal energy are found mainly in northern and southern Holland (Noord-Holland and Zuid-Holland), Noord-Brabant, and in the northern and eastern parts of the Netherlands. They include (**Figure 16.14**) Permian (Rotliegend) sandstones of the Slochteren Formation in northern Holland, Friesland, Drenthe and Groningen; Lower Triassic sandstones (the Main Buntsandstein Subgroup) in Zuid-Holland, Noord-Brabant, eastern Netherlands and Limburg; Lower Cretaceous sandstones in Zuid-Holland, Friesland and the eastern Netherlands, and shallow Tertiary sands (Brussels Sand Member and Breda Formation) at shallow depths countrywide. Their reservoir parameters and calculated Heat in Place (HIP) content are listed in **Table 16.8**. The observed average geothermal gradient of 30 to 32°C/km, in combination with the abundance of permeable aquifer sediments at depth ranges of 1500 to 4500 m, gives good potential for geothermal energy (Lokhorst & Wong, 2007) (**Figure 16.15**). The aquifers suitable for geothermal exploitation are the same as the oil and gas-bearing reservoirs, implying considerable overlap (see Chapter 15; Figure 15.5). The very shallow-depth, permeable Pleistocene aquifers that occur throughout the Netherlands are also used extensively for seasonal heat and cold storage.

Table 16.8 Geothermal characteristics of Dutch aquifers (after Lokhorst & Wong, 2007, based on Lokhorst & Van Montfrans, 1988 and Van Doorn & Rijkers, 2002).

Aquifer	Depth (m)	Gross sand thickness (m)	Porosity (%)	Permeability (mD)	Temperature (°C)	HIP (10^{18} J)
Permian, Rotliegend sandstones						
Groningen, Friesland, Drenthe & Noord-Holland	2000-4500	10-200	11-25	30-600	Max. 100	50
Lower Triassic sandstones						
West Netherlands Basin & Roer Valley Graben (Zuid-Holland & Noord-Brabant)	2000-4000	25-300	Variable	Variable	Max. 100	30
Lower Saxony Basin (locally)	2000-3500	Max. 80	Variable	Variable	Max. 100	3
Other areas	300->5000	0-50	Variable	Variable	Max. 100	4
Lower Cretaceous sandstones						
West Netherlands Basin (Zuid-Holland)	700-2500	Max. 250	15-30	10-3000	Max. 90	3
Lower Saxony Basin (especially SE Drenthe)	800-1800	10-65	15-20	220-500	40-80	0.4
NW Friesland	1800-2000	10-200	15-22	1-30	70-80	
Tertiary sands						
Brussels Sand Member	100-1150	0-135		Max. 600	15-45	
Breda Formation	<835	Variable	30-35	5-200		
Total Heat in Place						>90.4

Economic importance

The use of direct geothermal heat (down to depths greater than 3000 m) has recently attracted significant interest from private greenhouse enterprises and a number of city councils, housing co-operations and/or private town developers. It is expected that within the next few decades several tens of geothermal doublets will be developed for greenhouse and/or district heating purposes in the Netherlands. Expected capacities for these needs might range from a few MW up to more than 10 MW per doublet (around 50 000 to 150 000 GJ/year, based on 4000 running hours/year). The first exploration licence for this purpose was

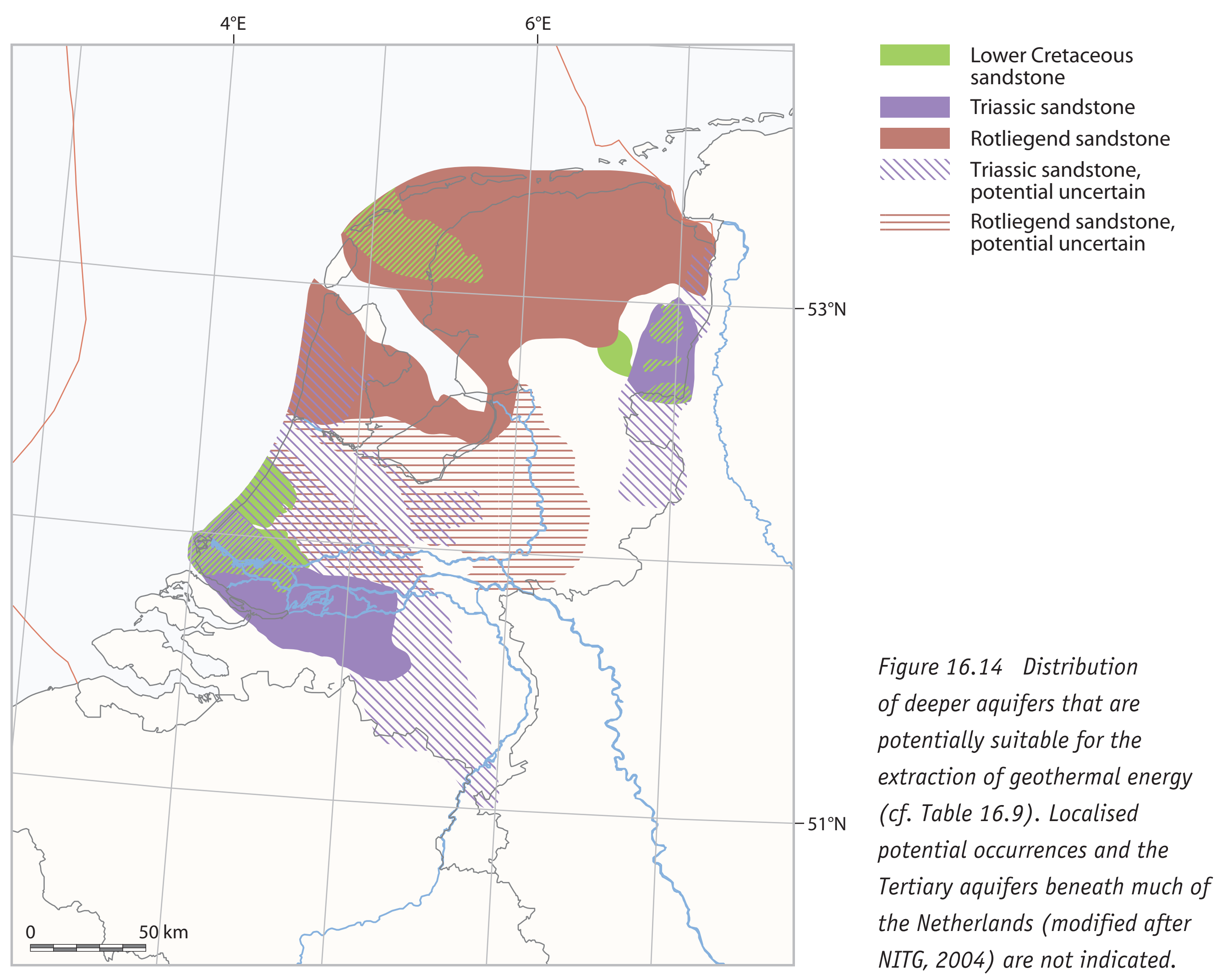


Figure 16.14 Distribution of deeper aquifers that are potentially suitable for the extraction of geothermal energy (cf. Table 16.9). Localised potential occurrences and the Tertiary aquifers beneath much of the Netherlands (modified after NITG, 2004) are not indicated.

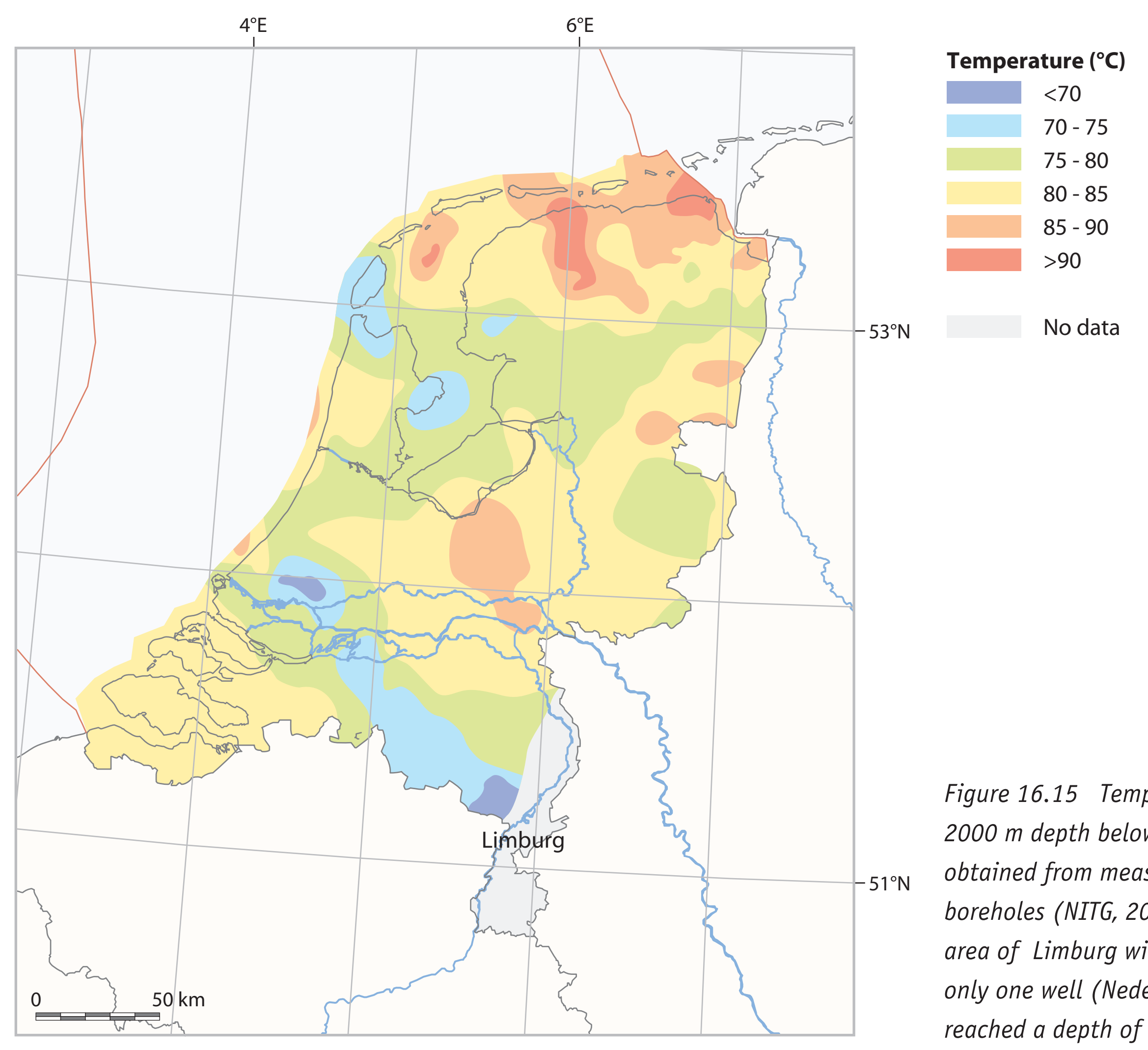


Figure 16.15 Temperatures at 2000 m depth below the surface, obtained from measurements in boreholes (NITG, 2004). In the area of Limburg with no data, only one well (Nederweert-1) reached a depth of 2000 m.

granted in 2006 to a greenhouse farmer in Bleiswijk (southern Holland). The outputs of the geothermal well were more than double the expectations (60°C, 160 m^3/hr). The first geothermal district heating grid was expected to be built south-west of The Hague in 2009. This doublet will serve around 4000 dwellings. Some 10 to 20 projects for direct use of geothermal heat are still underway, mainly in the western and northern Netherlands. Furthermore, water from relatively shallow depths of 400 to 750 m and temperature of 24 to 37°C from the Eocene Brussels Sand Member, Zechstein carbonate units and Dinantian Zeeland Formation limestones is locally used for balneological purposes, for example, at (Ameland Island, Nieuweschans (eastern Groningen), Arcen-Limburg (RGD, 1987) and Valkenburg (southern Limburg) (Krings & Langguth, 1987). Production rates from these systems are modest. Extraction of heat from water in the galleries and shafts of the former coal mines in southern Limburg (around 700 m depth) is also in progress (Demollin-Schneiders, 2007), but as the temperature of the water is less than 30°C, heat pumps will be required. Extraction and storage of heat and cold water using heat pumps is well established down to 500 m depth. A combined heat and cold-storage system uses groundwater in shallow aquifers (less than 500 m depth) as the main carrier of the energy. In this open circuit, water temperatures of 5 to 25°C and thermal power of 200 to 20 000 kW is applied in more than 700 systems (Van Heekeren, 2008). Closed-loop, ground-source heat-pump (GSHP) systems are used down to 150 m. They have a thermal power ranging from 50 to 100 kW and have recently gained increasing popularity: by the end of 2004, GSHP were operating in more than 1100 systems (Van Heekeren et al., 2005). In the near future, the deeply buried volcanic rocks and moderate to low-permeability clastic rocks of the upper and lower Rotliegend of the north-eastern Netherlands, Triassic aquifers in the Roer Valley Graben, and possibly even Lower Carboniferous limestones, might be feasible targets for application of Enhanced Geothermal Systems. Geothermal electricity can be generated from such systems, similar to current so-called 'Hot Dry Rock' projects in Germany and France.

Regulations and licensing

In the Netherlands, geothermal exploration and production from depths more than 500 m beneath the surface is regulated by the Dutch Mining Act (2003), for which the Ministry of Economic Affairs is the Permitting Authority. Permits/licences are required for exploration for terrestrial heat, production of terrestrial heat, and the operational plan during the entire process of geothermal mining activities (Van Heekeren, 2008). Geothermal applications below 500 m have to meet the criteria as defined in the Groundwater Act, which is governed by the 12 provinces. Furthermore, exploitation of both deep and shallow geothermal energy has to meet regulations within the Environmental Management Act (e.g. Environmental Impact Assessment). This Act regulates emissions to air, water and soil as well as of energy efficiency and sustainable energy system objectives.

3.4 Denmark

Tectonic units and geothermal regime

Four major structural features, the Danish Basin, the Sorgenfrei-Tornquist Zone, the Ringkøbing-Fyn High and the North German Basin, control the geothermal prospectivity of Denmark (**Figure 16.16**). The Triassic to Lower Cretaceous succession has a relatively uniform thickness in most of the Danish Basin, with some thinning towards the Ringkøbing-Fyn High where the Lower Jurassic, and parts of the Triassic, have been eroded. Subsidence gradually became more widespread again in late Mid- to early Late Jurassic times. The Sorgenfrei-Tornquist Zone is a strongly block-faulted zone with tilted Paleozoic fault blocks overlain by thick Mesozoic deposits, where, for example, thick paralic Upper Triassic and Jurassic sandstones were deposited and today form excellent reservoirs (Nielsen et al., 2004) (**Figure 16.17**). The temperature-depth relationship is rather uniform in the Danish area with an average gradient of about 30°C/km. The formation-water salinity gradually increases with burial depth, reaching total dissolved salts (TDS) of 300 g/l at 3200 m.

Geothermal systems

The most promising geothermal reservoirs occur in the Triassic to Lower Cretaceous succession (**Figure 16.17**) known from about 60 deep wells and seismic data. Several stratigraphic units with regional geothermal potential have been identified (Nielsen et al., 2004) (**Figures 16.16** & **16.17**). These include the Lower to Middle Triassic Buntsandstein Group and Skagerrak Formation, the Upper Triassic to Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation and the Upper Jurassic to Lower Cretaceous Frederikshavn Formation. Other formations may locally contain potential aquifers. The Buntsandstein Group occurs south of the Ringkøbing-Fyn High and locally on the high itself, and in the Danish Basin, and grades into the Skagerrak Formation towards the north-eastern basin margin. The Buntsandstein Group is dominated by fine-grained sandstones deposited mainly in an arid-continental environment dominated by fluvial channels, aeolian dunes and marginal-marine facies. The less well-known Skagerrak Formation occurs along the northern and north-eastern basin margin. The Buntsandstein Group is a promising geothermal reservoir with porosities of up to 24% and permeabilities of 10 to 100 mD. The Gassum Formation occurs in almost the entire area of Denmark and has remarkably uniform thicknesses, generally between 100 and 150 m, with a maximum of about 300 m in the Sorgenfrei-Tornquist Zone. The formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with

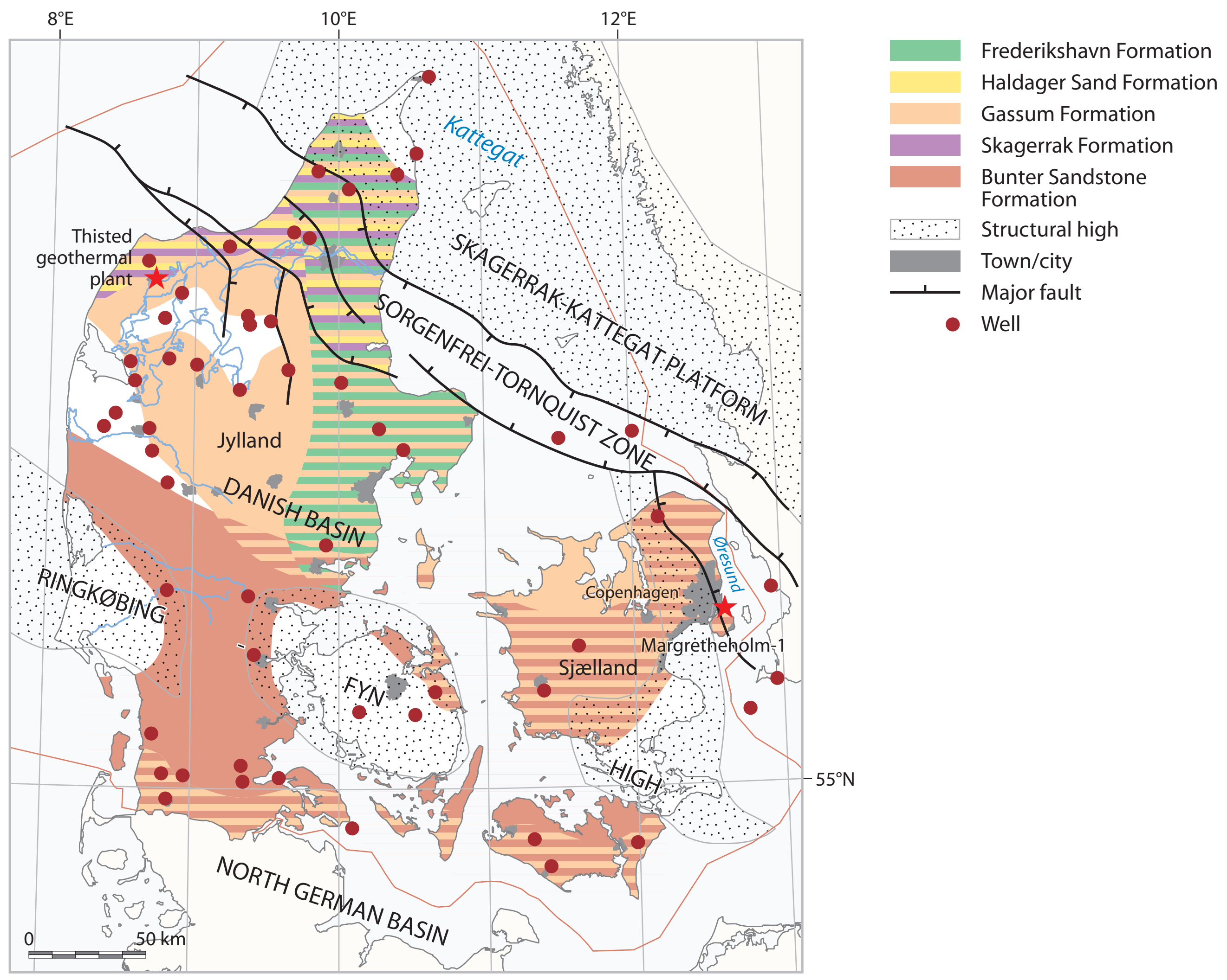


Figure 16.16 The regional geothermal potential of possible aquifer formations in Denmark, based on burial depths of 1000 to 2500 m and a sand thickness of more than 25 m. White areas in Denmark indicate that the reservoir is either not present (Ringkøbing-Fyn High), too shallow (northernmost Jylland), or too deeply buried (central Danish Basin). The locations of the Thisted geothermal plant and the new geothermal site at Margretheholm in Copenhagen are shown.

heteroliths, claystones and thin coals. The laterally continuous sandstones were deposited by repeated shoreline progradation. Fluvial and estuarine sandstones dominate the lower to middle part of the formation in the Sorgenfrei-Tornquist Zone. The reservoir properties are very good, with porosities between 18 and 27% and permeabilities up to 2000 mD. The Haldager Sand Formation is up to 200 m thick in the Sorgenfrei-Tornquist Zone, but thins markedly towards the south-west and north-east and consists of thick units of fine- to coarse-grained sandstones alternating with thin siltstones, claystones and coals deposited in shallow-marine, estuarine, fluvial and lacustrine environments. The Frederikshavn Formation occurs in the northern part of the Danish area and has marked thickness variations (75-235 m) reaching a maximum in the Sorgenfrei-Tornquist Zone. The formation consists of siltstones and fine-grained sandstones interbedded with claystones. The reservoir formations with most potential for geothermal applications are thicker than 25 m and occur at depths of 1000 to 2500 m.

Economic importance

The first Danish geothermal wells were drilled in 1979 into sandstone aquifers at 2000 to 3000 m depth (e.g. Hurter & Haenel, 2002). These deep, hot aquifers were tested by three wells in northern Jylland (**Figure 16.16**), but, as they had low permeabilities, interest shifted to the shallower aquifers with better porosities and permeabilities. There are two geothermal plants currently operating in Denmark (**Figure 16.16**) at Thisted (northern Jylland), where Gassum Formation sandstones at about 1200 m depth are the main reservoir, and at Margretheholm (near Copenhagen), where Buntsandstein Group sandstones at about 2700 m depth are the main reservoir. In 1988, using a low-cost absorption heat pump, the Thisted plant extracted 4 MW from 150 m^3/h of the geothermal water from a ~45°C warm 100 mD Gassum Formation sandstone aquifer; in 2001 it extracted 7 MW from 200 m^3/h of the 15% saline geothermal water (Mahler & Magtengaard, 2005). The newly opened Margretheholm plant has a 27 MW capacity and annual production is expected to be about 14 MW or 400 TJ heat. This corresponds to 1% of the total heating demand of the Copenhagen area, based on the utilisation of ~70°C geothermal water, but with an option for expansion. Geothermal exploration has now been resumed in other parts of the onshore Danish area, and the geothermal resources in known sandstone aquifers are today believed to be sufficient to supply household heating requirements in Denmark for more than a century.

Regulations and licensing

In 1983, Dansk Olie & Naturgas A/S (now DONG Energy) was granted a single concession for the exploration and production of geothermal energy covering the entire land area of Denmark. In 1993 and 2003, selected parts of the concession area were returned to the State in accordance with the licensing terms. DONG Energy is still the only company carrying out geothermal exploration and exploitation (Mahler & Magtengaard, 2005).

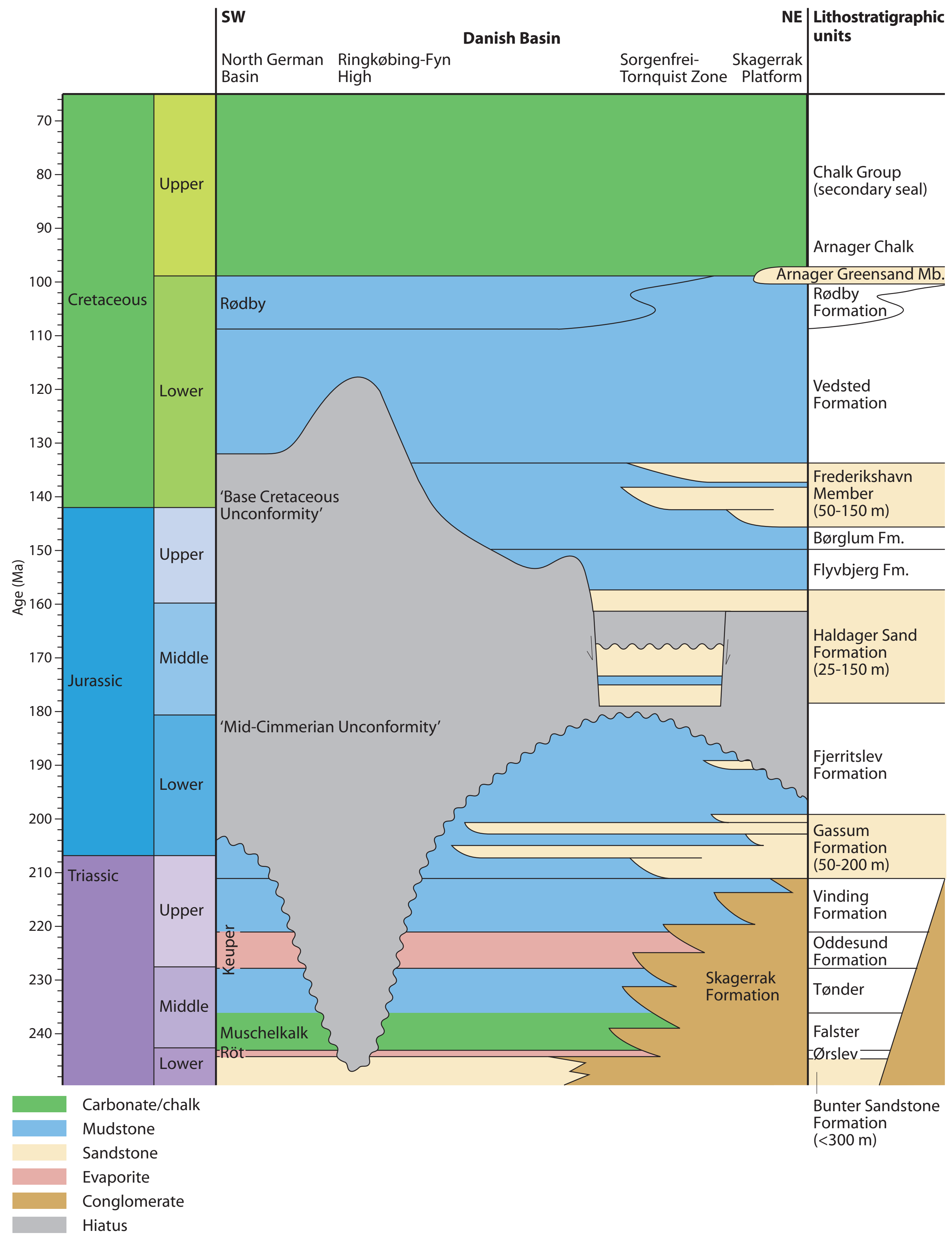


Figure 16.17 Generalised stratigraphic scheme of the Danish Basin showing formations with potential aquifers. Note the pronounced erosion surfaces at the base of the Middle Jurassic and Lower Cretaceous and the progressive onlap to these surfaces. These features have a major influence on the regional distribution and burial depths of potential reservoirs.

3.5 Germany

Tectonic units and geothermal regime

In the North German Basin, potentially commercial geothermal low-enthalpy hydrothermal systems are related to essentially Permian and Mesozoic to Cenozoic porous sandstones and sandstone aquifers (Wolfgramm et al., 2004; Feldrappe et al., 2007). The Permian (Stassfurt) carbonates are only suitable where local facies conditions are similar to Jurassic coral-oolitic limestones (Wolfgramm et al., 2004). Based on a number of parameters (**Table 16.9**) the most suitable aquifers for geothermal energy are (1) Rhaetian-Liassic reservoirs (2) Middle Buntsandstein Subgroup (3) Lower Cretaceous, (4) Rotliegend, and (5) Aalenian (Middle Jurassic) (Wolfgramm et al., 2004). The Rotliegend geothermal aquifers at the southern margin of the North German Basin are the deepest, reaching 4500 m, with temperatures up to 150°C (Feldrappe et al., 2007). The shallower Buntsandstein Group aquifers may be absent in places where salt piercements form domes or walls. Tertiary aquifers are formed by Rupelian and Eocene sands that are locally very deeply buried in rim-synclines adjacent to salt diapirs, where they have high temperatures (Seibt et al., 2006).

Table 16.9 Evaluation (scoring) of the geothermal aquifers in the North German Basin by temperature, reservoir parameters and extension (++: 3 scores, +: 2 scores; o: 1 score, ––: –2 scores).

Stratigraphy	Temperature		Porosity, permeability		Aquifer distribution		Evaluation	
	60-100°C	>100°C	60-100°C	>100°C	60-100°C	>100°C	Heat	Electricity and heat
Oligocene (Rupelian)	–	––	o	–	o	––	2	0
Eocene	–	––	o	–	o	––	2	0
Lower Cretaceous	++	o	++	+	+	o	8	4
Oxfordian (Korallenoolith)	+	––	–	–	–	–	2	0
Lower Callovian	+	–	++	o	+	o	7	2
Bajocian/Bathonian	+	–	+	o	+	–	6	1
Aalenian	+	–	++	+	++	o	8	3
Toarcian	+	–	+	o	+	o	6	3
Pliensbachian (Domerian)	+	–	+	+	+	o	6	3
Hettangian, L. Sinemurian	++	o	++	++	++	+	9	6
Keuper (Rhaetian)	++	o	++	++	++	+	9	6
Keuper (Stuttgart Fm.)	++	+	+	o	o	o	6	4
Keuper (Lettenkeuper)	++	+	o	o	o	o	5	4
Upper Buntsandstein	o	––	o	–	–	––	2	0
Middle Buntsandstein	++	++	++	o	+	o	8	5
Stassfurt carbonates	–	–	–	–	–	––	0	0
Rotliegend, Elbe Subgroup	++	++	+	o	o	o	6	5
Rotliegend, Parchim Fm.	++	++	+	o	o	o	6	5

Geothermal systems

The predominantly deltaic, up to 120 m-thick, Rhaetian to Liassic sandstones are the main geothermal aquifer in Germany (**Figure 16.18**); the sandstones have porosities of 20 to 35%, permeabilities of 0.5 to 1.0 D or higher, and productivities of 50 to 250 $m^3/(h \cdot MPa)$ (Feldrappe et al., 2007). The locally fluviatile Middle Buntsandstein Subgroup is also a geothermal reservoir and is 20 to 50 m thick with porosities of 10 to 30%, moderate to good permeabilities, and productivity of 100 $m^3/(h \cdot MPa)$. Lower Cretaceous reservoirs are 10 to 60 m thick with porosities of 20 to 30%, permeabilites of 0.25 to 1 D, and productivity of 50 to 250 $m^3/(h \cdot MPa)$ (Feldrappe et al., 2007). The Rotliegend aquifers in aeolian sandstones are suitable only along the southern basin margin, and have porosities of 15 to 25%, permeabilities of up to 0.25 D and productivity up to 50 $m^3/(h \cdot MPa)$. The widespread Aalenian sandstones are 30 to 100 m thick, have porosities of 25 to 35% and permeabilities of 0.5 to 1 D. The formation waters have salinities ranging from 100 to 300 g/l depending on the depth of the aquifer (Seibt et al., 2006).

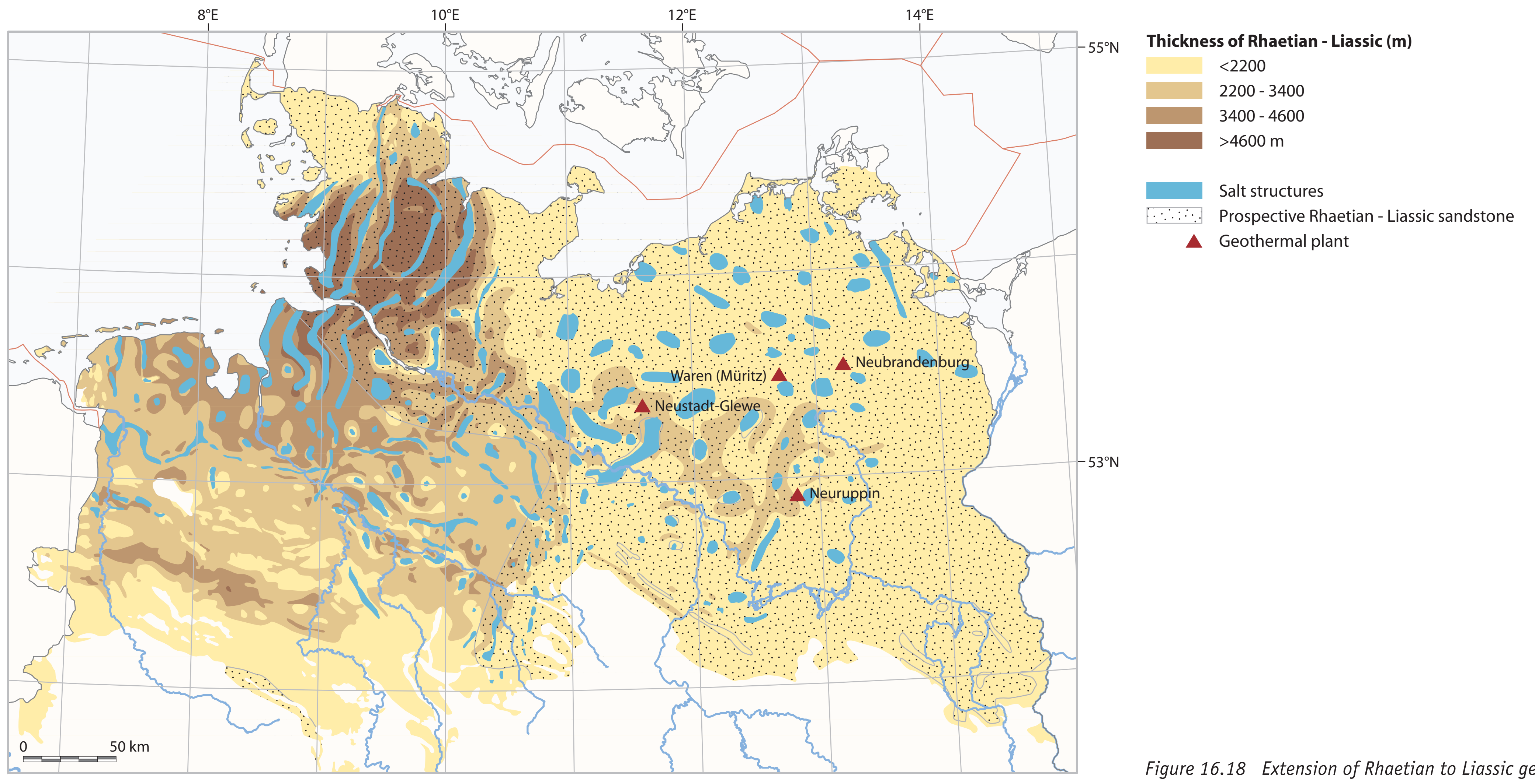


Figure 16.18 Extension of Rhaetian to Liassic geothermal aquifer complex.

Economic importance

The boundary conditions for commercial exploitation of low-enthalpy hydrogeothermal reservoirs are: effective porosity >20%; permeability >0.5 × 10^{12} m^2; thickness >20 m, and production flow rates of 50 to 100 m^3/h per well (Rockel et al., 1997). Furthermore, for electricity generation, reservoir temperatures must be more than 100°C, for heat production, more than 50°C, and for balneology the reservoir temperature must be more than 20°C.

The first geothermal heating plant (GHP) in Germany was commissioned in Waren (Müritz) in 1984. Since 2003, geothermal electricity has been produced by a pilot project at Neustadt-Glewe (Seibt et al., 2005). Both locations are in the North German Basin. Aquifers with the required high geothermal gradients for geothermal exploitation are only found in the Tertiary basin or graben systems of the Molasse Basin, Upper Rhine Valley and the Permian of the North German Basin. The GHP and aquifer thermal energy stores (ATES) at Waren (Müritz), Neubrandenburg and Neustadt-Glewe exploit Rhaetian sandstones. In the Rotliegend aquifers, geothermal energy is being exploited in for example the Barnim Depression (via wells Gross Schoenebeck 3 and 4). In 2007, a GHP was constructed at Neuruppin to exploit the Aalenian sandstone.

Regulations and licensing

The development of geothermal reservoirs in Germany is regulated by the Federal Mining Code. Applications for exploration permits and production must be submitted to the Mining Authorities of the relevant individual Federal State.

3.6 Poland

Tectonic units and geothermal regime

The two main tectonic units, the East European Platform and the Paleozoic Platform of central and western Europe (Pożaryski, 1974), have different geothermal regimes. In Poland, the most prospective reservoir units for geothermal energy are in the Szczecin, Warsaw and Mogilno-Łódź troughs (**Figure 16.19**). These form tectonic blocks where geothermal reservoirs occur at depths of 800 to 3500 m. Of minor importance are the Fore-Sudetic Region, Pomeranian Swell, Kujawy Swell and Lublin Trough, where geothermal reservoirs are found at shallower depths between 250 to 3500 m (Górecki, 2006a). Geothermal systems occur in several Lower Permian to Mesozoic formations. The main geothermal reservoirs that are feasible for exploitation are sandstones and, in some cases, Lower Cretaceous and Lower Jurassic carbonates, as well as Middle and Upper Jurassic and Lower and Upper Triassic reservoir formations. These reservoirs form regionally important geothermal systems (in the order of 100 000 to 200 000 km^2 in area). The depths and total thicknesses of particular formations vary, but depths up to 3000 to 4000 m are the present limit of economic and technical feasibility. The Mesozoic strata are the best explored for geothermal energy. Lower Permian reservoirs generally have unfavourable reservoir parameters, which result in low potential discharges (Górecki, 2006a). Nevertheless, good reservoir parameters and high temperatures were found in some Permian reservoirs (Hajto & Górecki, 2005).

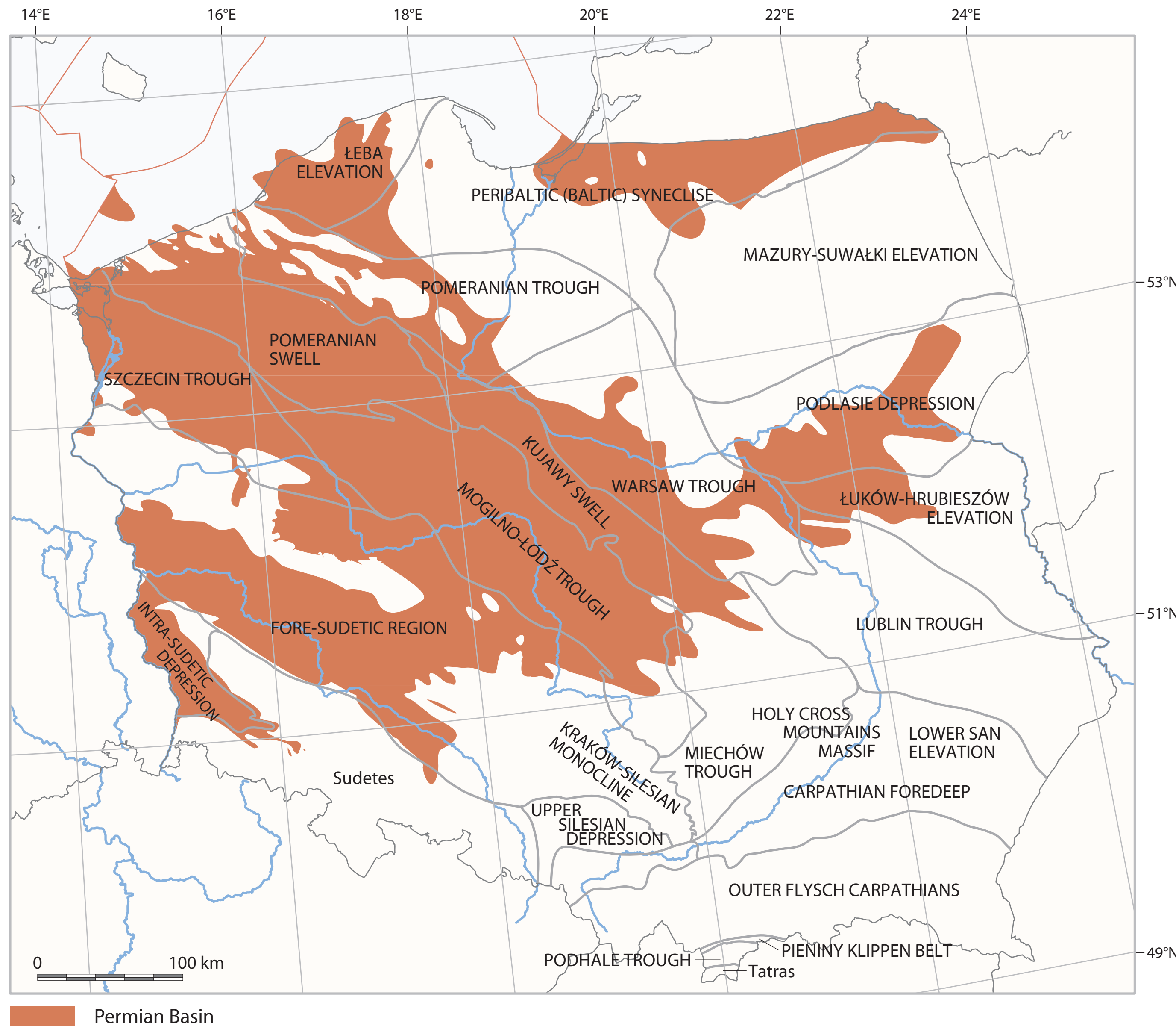


Figure 16.19 Structural units of Poland and the Permian Basin with geothermal systems according to Górecki (2006a). Geotectonic division after Pożaryski (1974).

Geothermal systems

Geothermal gradients vary between 1 to 4°C/100 m in the Permian Basin, which comprises about 87% of the Polish territory (Plewa, 1994). Reservoir temperatures range from 30 to 140°C at depths of 1000 to 4000 m (low-enthalpy geothermal resources). The region is characterised by varying low to locally medium terrestrial heat-flow values of about 35 to 105 mW/m^2 (Górecki, 2006a). The area of the East European Platform is characterised by lower heat-flow values of 35 to 55 mW/m^2, whereas the Paleozoic Platform of central and western Europe has distinctly higher and a wider range of values from 55 to 105 mW/m^2. The highest values (90 to 105 mW/m^2) occur in a 50 to 70 km-wide belt in the north-west of the Fore-Sudetic Monocline. Increased heat flow is also found in the central Kujawy Swell and in the central part of the Łuków Elevation. Geothermal-water flow rates change from several litres per second (l/s) up to 80 l/s and have hydrochemical zonation. Their total dissolved solids (TDS) generally increase with depth from 0.1 to more than 300 g/dm^3 and have very low TDS (often <1 g/dm^3) at depths below 1000 m. Deeper formations (Lower Jurassic, Triassic, Lower Permian) are affected by waters ascending from Zechstein salt series, which have very high TDS (even greater than 300 g/dm^3) and are dominated by Cl-Ca or Cl-Na brines.

Economic importance

Geothermal energy is commercially exploited principally from Lower Jurassic and Lower Cretaceous aquifers. The possibility of extracting geothermal energy from Lower to Upper Triassic, Middle Jurassic and Upper Triassic aquifers is low and related only to limited areas (Sokołowski, 1995; Górecki, 1995, 2006a). The total disposable resources of all Mesozoic aquifers are 6.3 × 10^{18} J/y (**Table 16.10**), which corresponds to an energy value of 150 × 10^6 TOE/y, whereas total disposable resources of the Lower Permian aquifer are 2.03 × 10^{18} J/y. The total disposable resources of geothermal energy that accumulated in the seven main geothermal aquifers of the Permian Basin (Lower Permian, Lower to Upper Triassic, Lower to Upper Jurassic and Lower Cretaceous) are 8.3 × 10^{18} J/y. Assuming the recovery of 1.5 to 2.5% of disposable resources, the exploitable resources of geothermal energy are estimated to be as high as 1.3 to 2.1 × 10^{17} J/y (3.0-5.0 × 10^6 TOE/y). Geothermal energy is used for domestic heating, agriculture, industrial applications, aquaculture, balneotherapy, curative treatment and recreation. The Permian Basin geothermal reservoirs are exploited in six localities in Poland (Kępińska, 2005) in both open and closed systems installed between 1996 and 2001. The heating plants in Mszczonów and Uniejów exploit the Lower Cretaceous reservoir and the Lower Jurassic aquifer at Pyrzyce and Stargard Szczeciński. Two spas (Ciechocinek and Konstancin) use geothermal waters from Jurassic sources. These aquifers are all found generally between 1400 and 2900 m depth and have reservoir temperatures ranging from about 30 to 90°C. Shallow geothermics using low-temperature waters or heat produced from shallow wells via heat pumps is common. Geothermal energy is also exploited by heat extraction from Zechstein salt-dome structures (Bujakowski et al., 2003). Within the deeper parts of the Permian Basin, where waters with temperatures more than 90°C are tapped, power and heat co-generation may continue with the use of binary schemes.

Table 16.10 Geothermal resources of the Permian Basin of Poland (based on Górecki, 2006a).

Aquifer	Area of calculation (km^2)	Resources: Static resources (J)	Static recoverabe (J)	Disposable resources: Area (km^2)	Energy (J/year)
Lower Createaceous	127 873	4.2×10^{20}	6.6×10^{19}	24 236	3.9×10^{17}
Upper Jurassic	197 842	2.4×10^{21}	3.0×10^{20}	7 409	2.5×10^{17}
Middle Jurassic	204 868	8.4×10^{20}	1.4×10^{20}	35 637	8.9×10^{17}
Lower Jurassic	160 398	3.0×10^{21}	5.6×10^{20}	81 390	1.9×10^{18}
Upper Triassic	178 150	1.2×10^{21}	2.4×10^{20}	29 776	1.1×10^{18}
Lower Triassic	228 758	2.7×10^{21}	6.1×10^{20}	38 839	1.7×10^{18}
Mesozoic		**1.1×10^{22}**	**1.9×10^{21}**		**6.3×10^{18}**
Lower Permian	101 913	1.7×10^{21}	4.5×10^{20}	28 613	2.0×10^{18}
Total		**1.4×10^{22}**	**2.3×10^{21}**		**8.3×10^{18}**

Regulations and licensing

Geothermal energy exploration, exploitation and use are regulated by the Geological and Mining Law, Economic Activity Law and Environmental Protection Law. The Geological and Mining Law (1994) defines the conditions for the exploration, exploitation and protection of geothermal resources. In line with the Economic Activity Law (1999) a concession is required from the Minister of Environment. According to the Environmental Protection Law (2001) concessions for prospecting, exploration and exploitation of geothermal waters should be preceded by evaluation of environmental impacts with the possible participation of local communities in the granting procedure.

4 Underground storage

4.1 CO_2 storage

4.1.1 United Kingdom

Geological and hydrogeological conditions

The most prospective CO_2-storage areas of the UK sector of the Southern North Sea Basin are east of the Dowsing Fault Zone and on the eastern margin of the Eastern England Shelf. Prior to gas production, this entire area was hydrostatically pressured.

Main geological areas for underground storage

The UK sector of the SPB appears to have excellent potential for the geological storage of CO_2 in conventional reservoir rocks (Brook et al., 2002; Holloway et al., 2006), as it has suitable reservoirs containing large structural closures interbedded with high-quality cap rocks. The main reservoir rocks are: Upper Carboniferous sandstone units at depth of more than 800 m; the (Early Permian) Leman Sandstone Formation and its onshore equivalent the Yellow Sands Formation (sometimes described as the Basal Permian Sands); the (Triassic) Buntsandstein Group and its onshore equivalent the Sherwood Sandstone Group; the Spilsby Sandstone Formation (Cretaceous) and the Chalk Group (Cretaceous). However, the CO_2-storage potential, particularly the reservoir characteristics, potential seals and structure of the Spilsby Sandstone Formation and the Chalk Group, has not been studied in detail, because only very few rocks in these formations are likely to be deep enough for CO_2 storage. The Carboniferous, Permian and Triassic gas reservoirs are the prime targets for CO_2 storage, whereas the Buntsandstein Group and possibly the Leman Sandstone are likely to be the most important for aquifer storage. The Leman Sandstone Formation consists mainly of porous and permeable aeolian and fluvial sandstones. Towards the basin centre, the formation passes laterally into lacustrine mudstones and evaporites of the Silverpit Formation and is extremely well sealed by the overlying thick Zechstein evaporites. The Buntsandstein Group contains several very large potential traps, only a few of which are gas-charged, which potentially could form CO_2-storage sites. The native pore fluid in most of these domes is highly saline water. There is little or no realistic CO_2-storage potential in coal seams in the UK sector of the SPB, mainly because of their low permeability (especially for increased lithostatic pressures at depths below 1500 m; Jones et al., 2004) and their potential importance as an energy mineral in the future.

Economic importance: perspectives and problems

The total quantified CO_2-storage potential of the UK sector of the SPB is up to about 18 Gt. This figure comprises the sum of estimates of the storage capacity in depleted gasfields and structural closures in apparently suitable saline aquifers. However, this estimate does not take into account the possibility that a proportion of the structural traps identified in the Buntsandstein Group aquifer may leak, or that pore-fluid pressure increase in the Buntsandstein Group, rather than its storage capacity in structural traps, may limit its storage capacity.

The total CO_2-storage capacity of the gasfields in the Buntsandstein Group is estimated to be approximately 0.434 Gt CO_2 (Holloway et al., 2006). Numerical simulation of CO_2 injection into one structure (Obdam et al., 2002; Obdam & Van der Meer, 2003) indicated that a maximum of 40% CO_2 saturation might be achievable, assuming infinite aquifer communication. The actual CO_2-storage capacity of the Buntsandstein Group might be considerably less than 14.25 Gt, because there is significant uncertainty about the integrity of some of the traps; seismically-derived maps indicate that many of them are cut by crestal faults.
The CO_2-storage capacity of the Carboniferous gasfields is estimated to be approximately 0.153 Gt. The Carboniferous aquifers have some favourable characteristics such as strongly heterogeneous lithologies (which would discourage migration of the injected CO_2) and, in the eastern UK sector of the basin, they are well sealed by the overlying Silverpit Formation and Zechstein evaporites. However, the CO_2-storage capacity of the Carboniferous aquifers could not be estimated due to the lack of relevant data. The storage capacity of the gasfields within Leman Sandstone reservoirs in the UK sector is estimated to be between 3.1 and 3.3 Gt. (Holloway et al., 2006). Potential issues for carbon capture and storage (CCS) as a greenhouse-gas mitigation option are principally the additional cost of capture, compression, transport and storage, and uncertainty about the leakage potential of geological storage sites. The 20 largest UK sources emit about 122 Mt CO_2 (Brook et al., 2002); if adapted for CCS, some 150 to 170 Mt of CO_2 could be available for storage annually.

Regulation and licensing

There are no specific regulations currently covering the geological storage of CO_2 in the UK. However, the EU Directive on CCS proposed by the European Commission on 23rd January 2008 (the CCS Directive) will be implemented in the UK. The inclusion of CCS as a valid means of emission reduction in the European Union Emissions Trading Scheme (EU ETS) is under consideration. An amendment has been made to the Protocol to the London Convention that allows CO_2 storage in subsea geological formations, and a similar amendment to the OSPAR Treaty is likely to be ratified in the near future.

4.1.2 Belgium

Geological and hydrogeological conditions

Due to the lack of depleted oil and gas reservoirs in Belgium, any underground storage of CO_2 will either be in deep saline aquifers or in coal layers. Storage in deep coal layers is possible in both the Campine and the Hainaut basins. There are expected to be only limited deep aquifer-storage sites to the north of the Brabant Massif and in the Hainaut area (**Figure 16.20**). The most prospective area is the Campine Basin and the adjacent Roer Valley Graben, where four deep saline aquifers have been identified: these are the karstified reservoirs within the Carboniferous Limestone Group, sandstones of the upper Westphalian Neeroeteren Formation, coarse-grained beds within the Buntsandstein Group and porous Upper Cretaceous and Lower Tertiary chalk arenites (Laenen et al., 2004) (**Table 16.11**).

Main geological areas for underground storage

The deep coal layers have low permeabilities. Measurements on coal samples from the Campine Basin give *in situ* values in the range 0.7 to 0.01 mD. The highest CO_2-storage potential in aquifers is assigned to the Buntsandstein Group reservoir unit in the Roer Valley Graben and the Campine Basin (**Figure 16.20**) where Mesozoic claystones and Cretaceous marls may provide adequate sealing. There may also be storage potential in Westphalian D Neeroeteren Formation sandstones in the north-east Campine Basin and the southern graben area, where sealing may be provided by Upper Paleozoic or Triassic claystones or by Cretaceous strata. Reservoirs in the Lower Carboniferous limestones and dolomites of the western Campine Basin may be combined with carbonate reservoirs within the underlying Devonian sequence. As has been proven by the UGS facility at Loenhout (**Figure 16.20**), the Namurian claystones and Westphalian coals and claystones provide adequate sealing.

Economic importance: perspectives and problems

The feasibility of CO_2 injection in the low-permeability coals of the Belgian coal basins remains to be proven. Tests that will be carried out at Geleen will be crucial in providing information about the Coal Measures storage potential. Apart from the poorly explored Buntsandstein Group, there is only limited storage capacity in aquifers, and they are suitable for only small-scale sequestration of CO_2 (in the order of a few to a few tens of millions of tons). In southern Belgium, storage possibilities are limited to the Hainaut area where karstified and collapsed rocks of the Carboniferous Limestone Group and overlying strata may have created reservoirs suitable for CO_2 storage. There are permeable beds within the

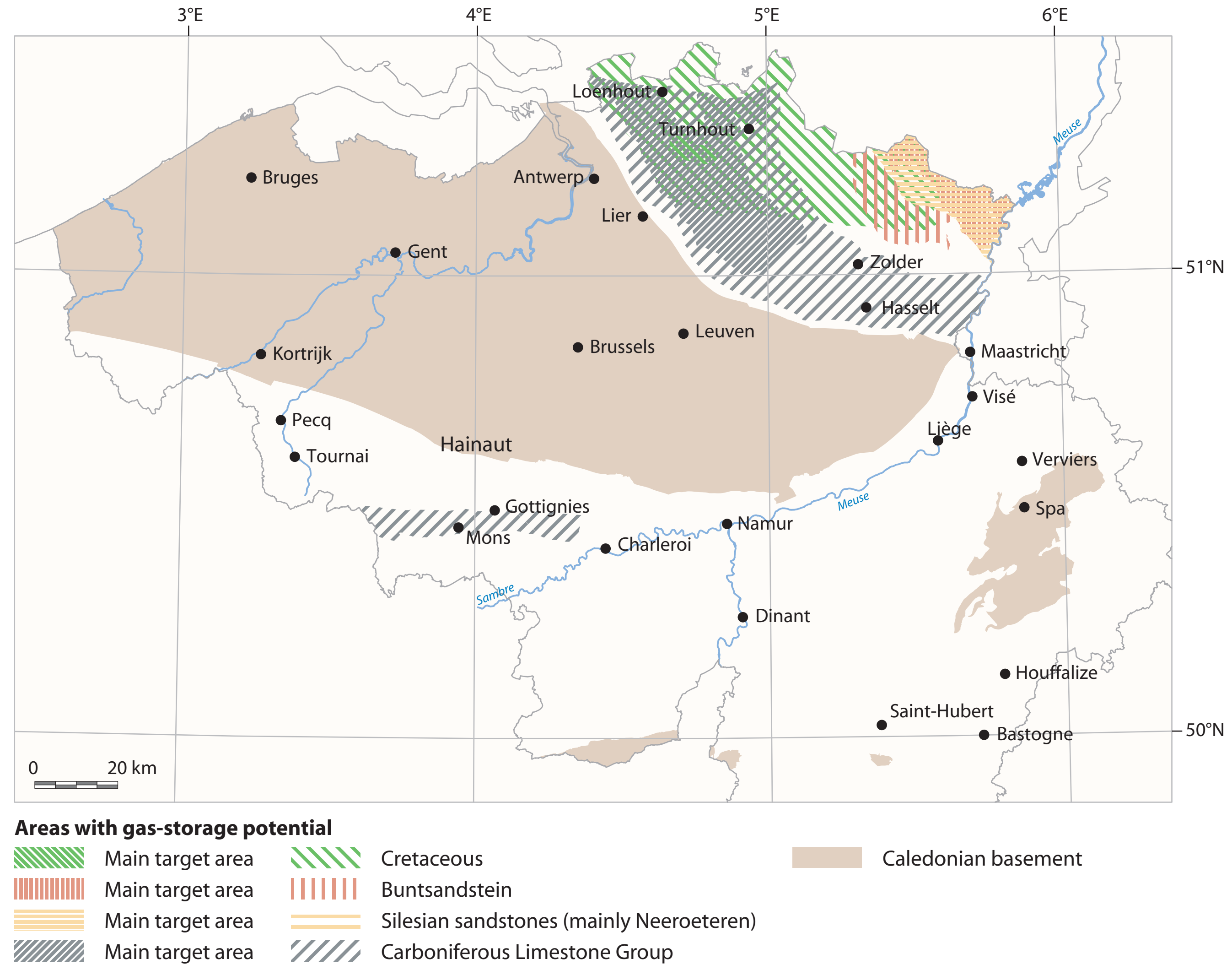


Figure 16.20 Areas with suitable reservoirs for potential UGS facilities in Belgium.

limestone series at Saint-Ghislain, Douvrain and Ghlin. However, the poor-quality data, the lack of a hydrological model for the area, and the unclear nature of sealing, have so far made it impossible to assess the storage potential of the region.

Regulations and licensing

UGS is regulated by the law of 18 July 1975 concerning the exploration and the exploitation of natural reservoirs for UGS. However, this law was drawn up to regulate the temporary storage of gas for energy supplies rather than the permanent underground storage of CO_2. Under a new decree (January 2009) concerning the exploration and exploitation of hydrocarbons and the underground storage of CO_2, the Flemish Government confirmed that CCS is the responsibility of the regions. The new Flemish decree provides a clear regulatory framework for CCS in Flanders. For monitoring and safety issues, it relies heavily on the guidelines stipulated in the European Directive on CCS.

Table 16.11 Reservoir properties and CO_2-storage potential for selected sites in the Campine Basin and the adjacent Roer Valley Graben (after Laenen et al., 2004).

	Karstified carbonates	Westphalian Coal Measures	Neeroeteren sandstones	Buntsandstein	Chalks
Geological characteristics					
Lithology	Limestones and dolomites	Coal	Sandstones	Sandstones	Calcarenites
Age	Dinantian (extending into Tournaisian and Devonian)	Westphalian	Westphalian D	Early Triassic	Late Cretaceous – Early Tertiary
Location	West Campine Sub-basin	Campine Basin	Roer Valley Graben	Roer Valley Graben	Northern Campine Basin
Type	Aquifer	Adsorption on coal (ECBM)	Aquifer	Aquifer	Aquifer
Reservoir characteristics					
Depth (m)	800-2300	500-1500	800-2000	800-2000	750-800
Temperature (°C)	40-150	30-65	-	-	-
Porosity (%)	1-20	<1-5	6-20	5-20	≤30
Permeability (mD)	2-3000	1-0.1	0.1-1100	0.3-400	≤500
CO_2-storage potential					
Total volume (Mt CO_2)	130	400	-	>880	Limited
Remarks	Several small reservoirs; small-scale storage facilities	Small ECBM fields; limited storage facilities in mine	Small-scale storage facilities; needs further investigation	Large storage volume; needs exploration	Limited storage facilities

4.1.3 The Netherlands

Geological and hydrogeological conditions

Depleted oil or gasfields and deep saline aquifers are potential sites for CO_2 storage in the Netherlands. **Figure 16.21** shows the locations of hydrocarbon fields and aquifer traps that have been identified as having potential for CO_2 storage and coalfield areas that could be used for Enhanced Coal-Bed Methane (ECBM) production. Dutch hydrocarbon fields mainly contain gas, proving that the geological structures have the capacity to trap gas. As a result, they are the most likely option for national (and international) CO_2 sequestration. Deep saline aquifers are commonly found in fault-controlled structural traps, but also in simple dip closures. During compilation of this inventory, the main focus has been on sandstone reservoirs overlain by claystone or shales and preferably rock-salts (Van Egmond, 2006). The most promising reservoir rocks for CO_2 storage are Slochteren Formation sandstones (Permian upper Rotliegend Group) sealed by Zechstein salt; Main Buntsandstein Formation sandstones (Lower Germanic Trias Group) sealed by salt or claystones, and sandstones of the Vlieland Sandstone Formation sealed by the Vlieland Claystone of the Lower Cretaceous Rijnland Group. Gross thicknesses of these sandstones range from 50 to 300 m in all three reservoirs and they are found at depths between 1000 and 4500 m. Formation-water salinity in the Dutch sandstone units varies significantly, from around 60 000 mg/l in the southern onshore/offshore Netherlands, up to 350 000 mg/l in parts of the northern offshore sector. These very high salinities are seen mainly in Paleozoic and Mesozoic rocks in areas close to Zechstein and Triassic evaporates, which have been affected by salt diapirism (Verweij, 2003). Overpressures in the Dutch reservoir units generally increase from close to hydrostatic in the southern offshore and adjacent onshore areas, to some 200 bar locally in the northern offshore sector. In the Terschelling Basin and Central Graben areas, the overpressures are even as high as 400 bar in Mesozoic rocks (Simmelink et al., 2008; Verweij et al, 2008).

Main geological areas for underground storage

Only depleted hydrocarbon fields and aquifer traps at a depth of at least 800 m are considered for CO_2 storage. Below this depth, the pressures and temperatures favour CO_2 in a super-critical state. A minimum capacity of 4 to 5 Mt is required to be economical; smaller hydrocarbon fields or traps are considered to be sub-economic. Almost 150 hydrocarbon fields have been selected as potential storage sites with an estimated storage capacity of 4 Mt or more (**Figure 16.21**).

Economic importance: perspectives and problems

The effective storage capacity in Dutch oilfields is estimated to be between 0.05 and 0.2 Gt Mt. The total effective storage capacity (Bachu et al, 2007) in the gasfields is estimated to be about 2.5 Gt. So far, the giant Groningen gasfield has not been considered for CO_2 storage because it will continue to produce gas until at least 2050; however, the gasfield could provide an additional storage volume of 7.5 Gt (Simmelink et al., 2007). Shell has advanced plans to use the Barendrecht gasfield near Rotterdam as a CO_2-storage test site, where they will inject 0.1 Mt CO_2 per year starting in 2010. Most fields become pressure-depleted during gas production, indicating lack of aquifer support. This implies that storage volume in aquifers can only be created due to the compressibility of rock and formation water. The volume that is created, the so-called storage-efficiency factor, is determined to be in the order of only 0.5 to 2%, which indicates that the total effective storage capacity for aquifers is about 0.1-0.5 Gt. The injection of CO_2 may also be used in upstream petroleum-industry activities for the enhanced recovery of oil and gas (Enhanced Oil Recovery (EOR) (see **Figure 16.25**) and Enhanced Gas Recovery (EGR)).

CO_2 sequestration in salt caverns seems unpractical and sub-economic in the Netherlands, as the maximum volume per cavern (~500 000 m^3) would allow only about 0.35 Mt of super-critical CO_2 to be injected. This is equivalent to the storage capacity of a very small gasfield of about 0.2 bcm. Injection of CO_2 in coal seams can be combined with the production of coal-bed methane (Van Bergen et al., 2007). Coal-bed methane production could become a viable option in the Netherlands and is preliminary foreseen as a possibility in the province of Limburg (Van Bergen et al., 2004). However, the associated CO_2-storage capacity is thought to be only a fraction of the capacity of depleted gasfields. A first field test for underground sequestration of CO_2 has recently started in a near-depleted Rotliegend reservoir at the K12-B gasfield owned by Gaz de France (**Figure 16.21**). Other tests are planned near Drachten (Friesland), with CO_2 being stripped from the flue gas and subsequently injected into a producing gasfield in the nearby Akkrum concession.

Regulations and licensing

The relevant laws governing CO_2 storage in the Netherlands are the Mining Act (MA) and the Environmental Management Act (EMA). The MA is important in the legal framework of CO_2-storage activities because it includes the most appropriate management tools and instruments for the deep subsurface, risk management and liability issues. An Environmental Impact Assessment (EIA) will be a mandatory requirement for underground CO_2 storage. The National Waste Plan (LAP), one of three regulations in the Environmental Management Act, clearly states that CO_2 is classified as waste when it is stored underground instead of being released into the atmosphere. However, it has been decided that the LAP is temporarily not applicable to CO_2 storage. Stored CO_2 will not be considered as waste once the CCS Directive is enforced. Further details on the legal situation in the Netherlands prior to implementation of the EU Directive can be found in AMESCO (2007). In cases where CO_2 originates from outside a working mine, the Dutch Provinces are considered to be the competent authority. When the CO_2 originates from within a working mine, as in the case of some of the current pilot projects, the Ministry of Economic Affairs is the responsible authority. It has not yet been clarified who will be the competent authority once the CCS Directive has been implemented.

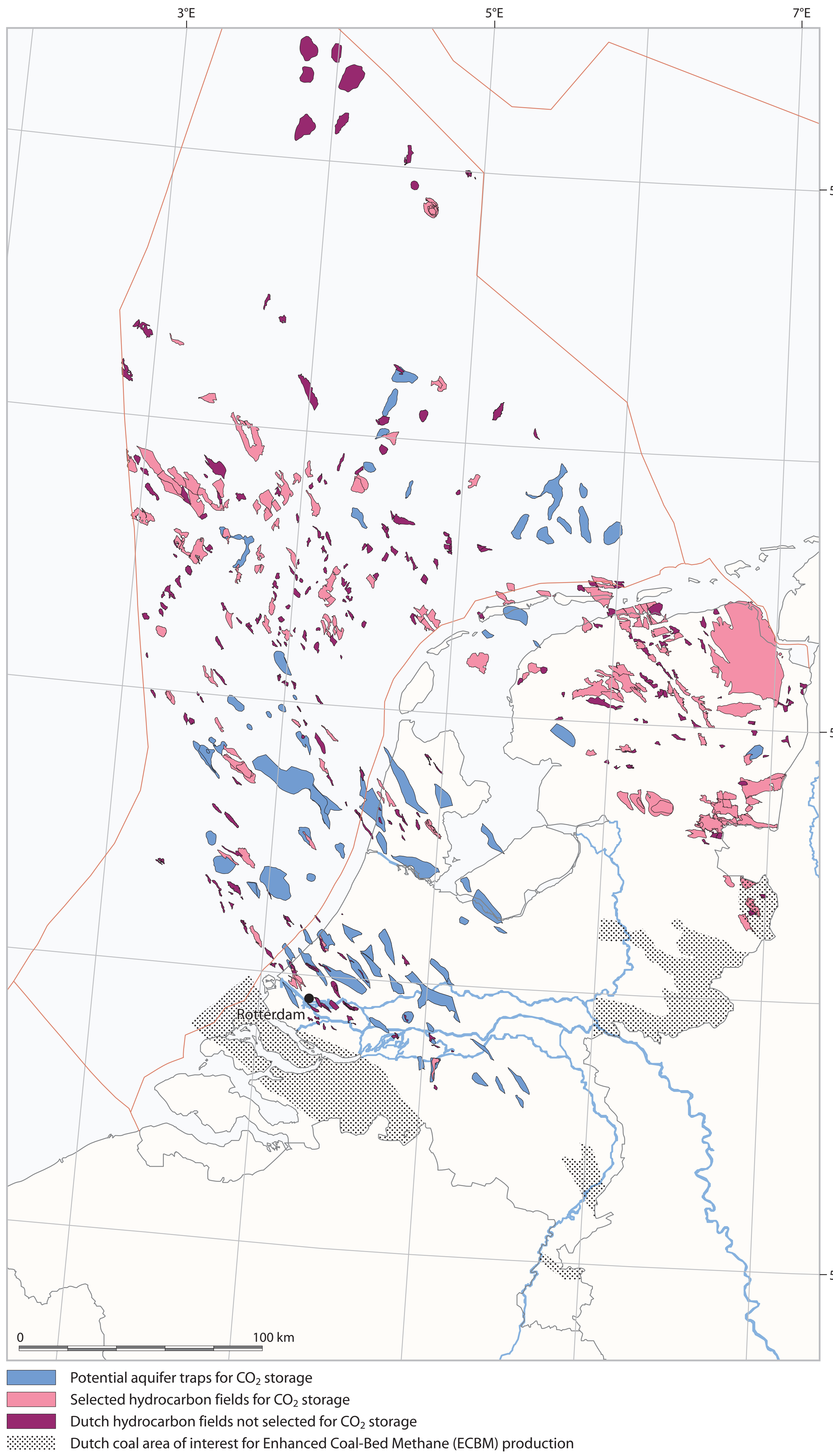


Figure 16.21 Potential CO_2-storage sites in the Netherlands.

4.1.4 Denmark

Geological and hydrogeological conditions

The deep saline aquifers that have been mapped for geothermal exploitation (see Section 3) could also be used for CO_2 and natural-gas storage, providing there is a suitable closure and seal or caprock (**Figure 16.22**). The suitable structures for natural-gas storage mapped in the 1980s, and more recently for CO_2 storage, are summarised in **Table 16.12** and **Figures 16.22** & **16.23** (Christensen & Holloway, 2003; Larsen et al., 2003). Possible sites for CO_2 storage are constrained by high porosities and permeabilities as found in sandstones and chalk; a minimum depth of 900 m and minimum pressures of about 80 bar are required for the CO_2 to be a super-critical fluid with viscosity as a gas and volume of only 1% of the gas.

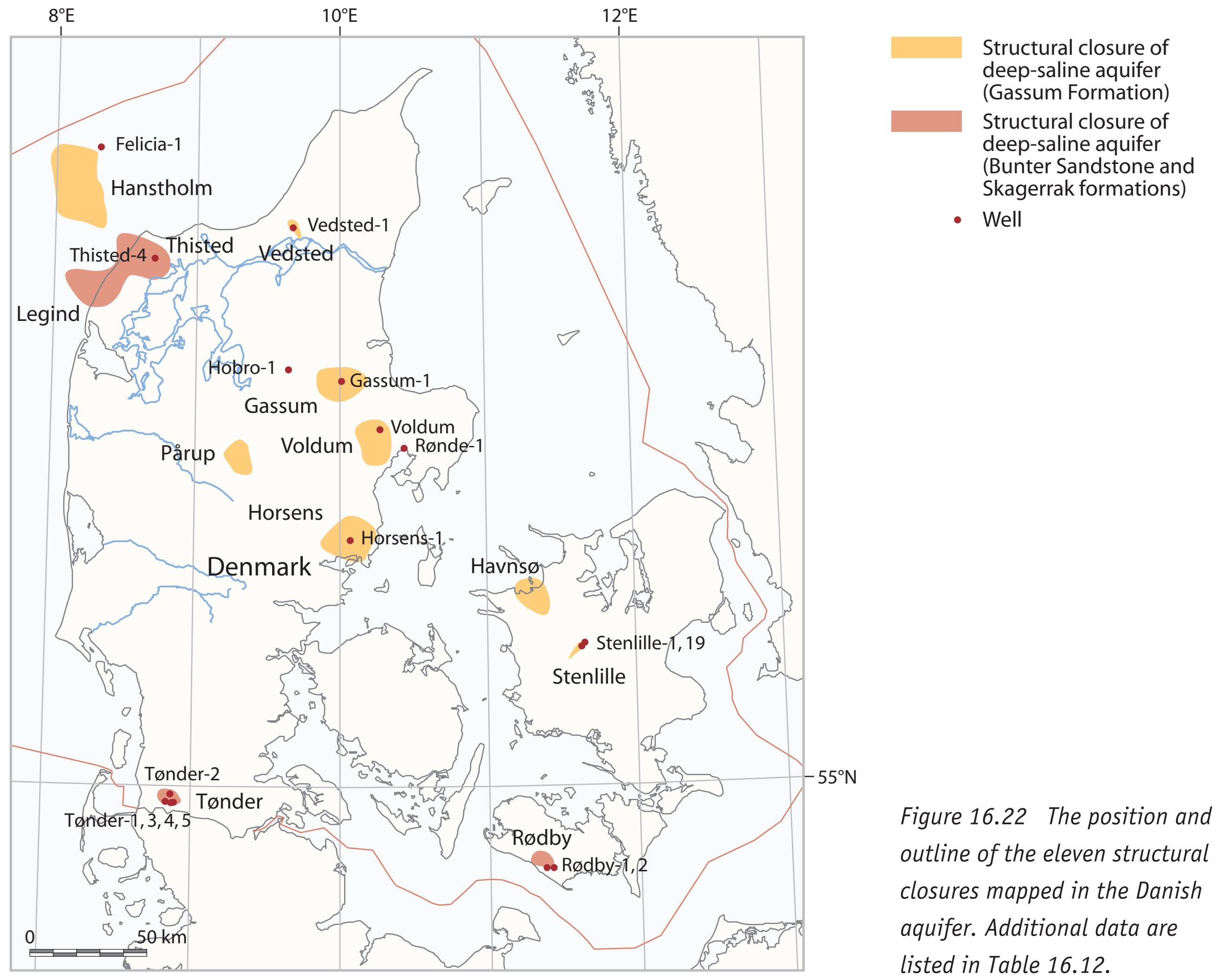


Figure 16.22 The position and outline of the eleven structural closures mapped in the Danish aquifer. Additional data are listed in Table 16.12.

Table 16.12 CO_2-storage capacity of major aquifer structures in Denmark.

Structure	Formation	Area (km^2)	Top depth (m)	Net sand (m)	Porosity (%)	Pore volume (km^3)	Reservoir density of CO_2 (kg/m^3)	Storage capacity (Mt CO_2)
Gassum	Gassum	242	1460	42	25	2.5	627	631
Hanstholm[1]	Gassum	603	1000	92	20	11.1	620	2 752
Havnsø[1]	Gassum	166	1500	100	22	3.7	629	923
Horsens	Gassum	318	1506	24	25	1.9	630	490
Pårup[1]	Gassum	121	1550	30	10	0.4	625	90
Rødby	Bunter Sandstone	55	1125	46	24	0.6	620	151
Stenlille[2]	Gassum	8	1507	99	25	0.2	631	50
Thisted/Legind	Skagerrak	649	1166	454	15	44.2	625	11 039
Tønder[3]	Bunter Sandstone	53	1615	35	20	0.4	626	92
Vedsted	Gassum	31	1898	103	20	0.6	633	161
Voldum	Gassum	235	1757	49	10	1.1	630	288
Total storage capacity								**16 667**

1 Extrapolated values.

2 A natural gas-storage facility operated by DONG.

3 Reserved for natural-gas storage. Based on Larsen et al. (2003b).

Main geological areas for underground storage

Deep saline aquifers are found onshore or nearshore Denmark in the extensive porous sandstone layers of the Lower Triassic Buntsandstein Group Formation/Skagerrak Formation, the Upper Triassic to Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation, and the Upper Jurassic to Lower Cretaceous Frederikshavn Formation (**Figures 16.16** & **16.22**). The distribution and descriptions of these units is given in relation to hydrocarbons and geothermal reservoirs in Chapter 13 and in Section 3. The sandstone units occur at depths of 900 to 2500 m, between the depth required for CO_2 to become a dense fluid and the depth below which reservoir quality typically deteriorates due to diagenetically induced reduction of porosity and permeability. The most important sealing rocks are mudstones of the Fjerritslev Formation, which stratigraphically occur just above the Gassum Formation and have almost the same areal distribution (**Figure 16.23**). The marine mudstones were deposited in a shelf environment and are between 100 to 500 m thick. The depleted oil and gas reservoirs in the Danish North Sea are also potential sites for CO_2 storage; after many years of exploitation, their geology is well known. However, as the oil and gasfields are located far from the major CO_2 point sources on land (e.g. power plants), this obvious possibility has only recently been assessed in more detail (Andersen, 2003).

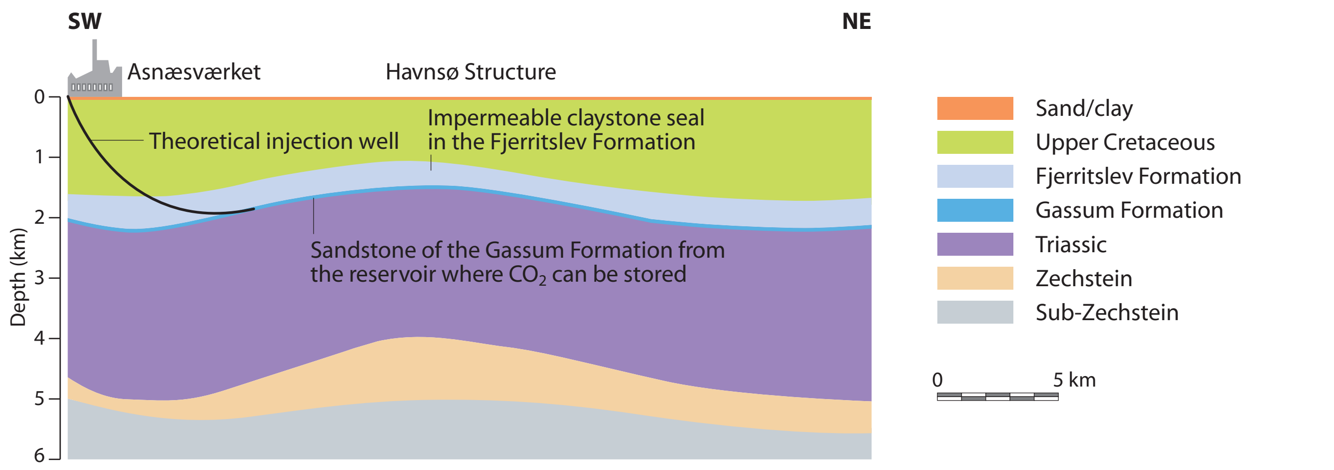


Figure 16.23 Cross-section of the Havnsø structure near the Asnæsværket, Kalundborg (see Figure 16.18 for the location of the field). The high-porosity sandstone layer formed by a rising salt pillow is situated about 1500 m beneath the surface and has an area of 160 km^2. The storage capacity is calculated to be about 900 Mt CO_2 (Table 16.12).

Economic importance: perspectives and problems

The storage capacity of hydrocarbon reservoirs is estimated to be 629 Mt CO_2 in existing oil and gasfields, 452 Mt of which can replace natural gas, and 176 Mt can replace oil (Christensen & Holloway, 2003). All of the fields investigated in the Danish North Sea are still in the production phase, and CO_2 injection will probably not be possible in the near future unless applied through Enhanced Oil Recovery (EOR) operations (Olsen, 2007) (e.g. in the USA and Canada, CO_2 injection can increase oil recovery by up to 15% in oilfields that are almost depleted). The potential storage capacity of deep saline aquifers is many times greater than that of hydrocarbon structures (Andersen, 2003). The total storage capacity of unconfined deep saline aquifers in Denmark has been estimated to be 47 Gt CO_2, although only a small volume was related to structural closures. It is assumed that 40% of the total pore volume within a trap could be filled with CO_2. Initial calculations suggest that the 11 structures that have been identified as potential CO_2-storage sites may provide storage for at least ~17 Gt CO_2 (**Table 16.12**). In Denmark, ten power plants produce 21 Mt CO_2 per year or 74% of the total CO_2 from all point sources (**Table 16.12**). Based on these calculations, there is enough underground volume to store several hundred years of total CO_2 emissions in Denmark (Christensen & Holloway, 2003). Several CCS projects have been initiated in the last few years, assessing both economic aspects of separation, transport and storage, and technical aspects of optimising the CO_2 separation processes (**Figure 16.24**; Larsen et al., 2007).

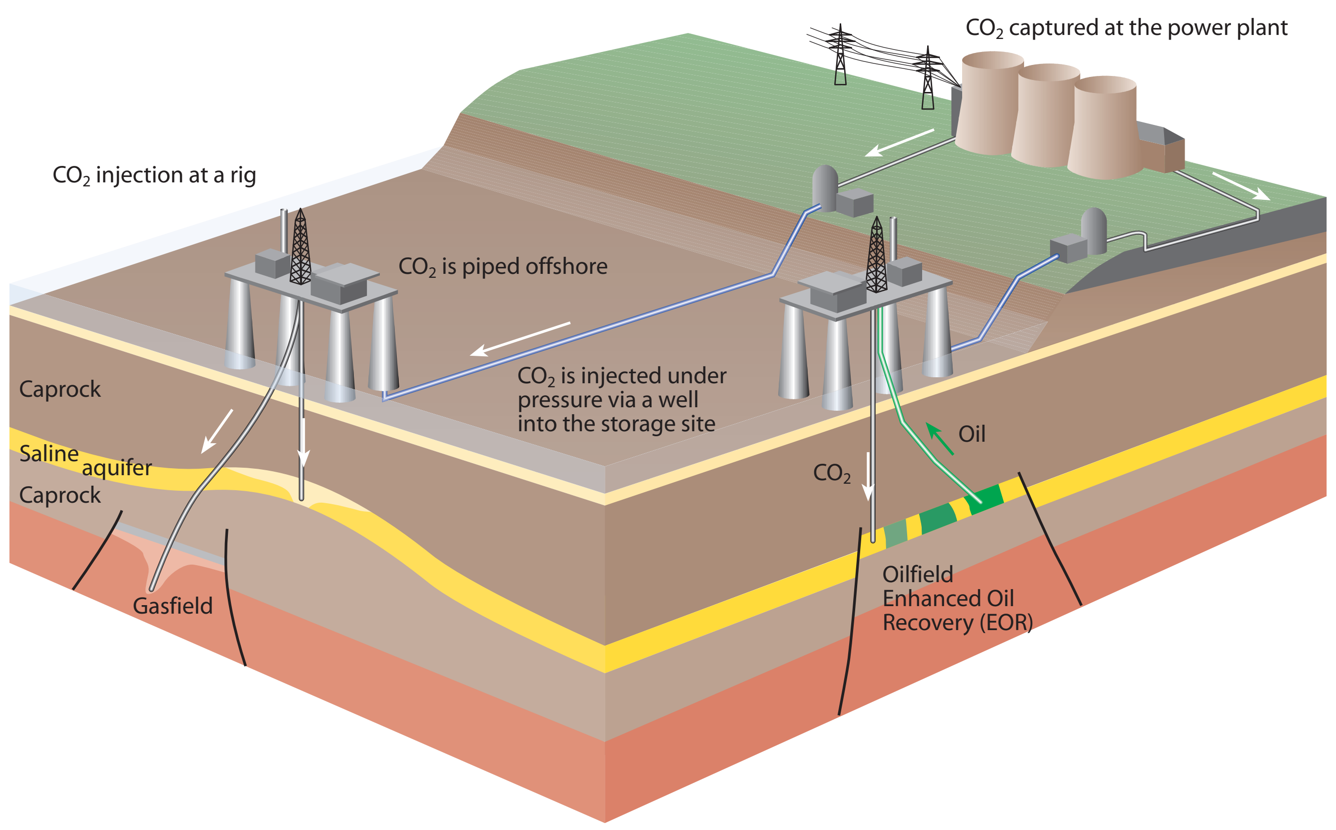


Figure 16.24 Schematic diagram showing the process of CO_2 capture and storage.

In the near future, CCS projects with demonstration plants will require new seismic data and wells to improve the knowledge of their feasibility for CO_2 storage in the Danish subsurface. It has also been shown that production of geothermal energy and storage of CO_2 can be combined if CO_2 is dissolved in the return-water. This is currently being assessed in two Danish geothermal plants (Mathiesen et al., 2003). Injection of CO_2 has been tested, for example, in the Sleipner field, where the produced gas contained 9% CO_2. Using CO_2 separation, the content has been reduced to 2.5%; the rest of the CO_2 is stored in the Middle to Upper Miocene Utsira Formation 1000 m below the sea bed, which is covered by about 250 m of plastic claystone.

Regulations and licensing

Storage of CO_2 in the Danish subsurface is by permission of the Minister of Climate and Energy pursuant to section 23 of the Act on the Use of the Danish Subsoil. A more detailed licensing system for storage of CO_2 will be implemented in conjunction with the CCS Directive.

4.1.5 Germany

Geological and hydrogeological conditions

Natural gas is stored in deep saline aquifers and depleted hydrocarbon reservoirs at several locations in Germany (**Figure 16.25**). The other main underground CO_2-storage option is coal seams that are not suitable for mining (**Table 16.17**). Storage in residual mine volumes may have limited potential in the Aachen, Ruhr, or Saar mining districts only (May et al., 2003). At CO_2-storage depths of about 1000 to 4000 m, the salinity of formation waters ranges from 100 to 400 g of dissolved salts per litre.

Main geological areas for underground storage

Most of the sandstones with good porosity and permeability are found in formations in northern Germany (May & Krull, 2003), the Upper Rhine Graben, and parts of the Alpine Molasse Basin (May & Turković, 2003). There may be minor potential for storage in deep parts of the Thüringian Basin and other smaller basins (**Figure 16.25**). The important sealing rocks in northern Germany are the widespread Zechstein rock-salt formations above the Rotliegend and lower Zechstein reservoirs, the Röt clay and salt deposits overlying the Buntsandstein Group, and the Paleogene (Oligocene) Rupel Clay Member, which often separates fresh groundwater above from saline water below (**Figure 16.26**). In the North German Basin, salinities below 1000 m depth commonly range from 100 to 300 g/l.

Economic importance: perspectives and problems

The CO_2-storage capacity of the 13 largest oilfields in Germany is only about 130 Mt, although gas reservoirs have significantly more potential. Taking a value of 2 bcm of accumulated gas production as a minimum for economical CO_2 storage, there are 39 fields of suitable size in northern Germany. The total natural-gas volume is equivalent to 2180 Mt of CO_2 under initial reservoir conditions. If both the known and probable reserves are included, the storage capacity increases to about 2750 Mt. The storage potential of the largest field, Altmark, is about 600 Mt, although the field capacity is less than 100 Mt (**Figure 16.27**). All of the hydrocarbon reservoirs of sufficient size to be considered for industrial storage projects are located within the North German Basin with the exception of one gasfield in Thüringia.

The largest volumetric storage potential could be provided by deep saline aquifers. The volumetric storage capacity of saline aquifers onshore Germany is estimated to be 20 ± 8 Mt of CO_2. The actual amount of CO_2 that can be injected into an available aquifer further depends on the maximum storage pressure permitted, reservoir management and well design. More realistic estimates of the national aquifer-storage capacity will have to consider other, as yet unknown, geotechnical, economical or legal boundary conditions, which will probably reduce the volumetric capacity further (May et al., 2005). There is considerable uncertainty about the CO_2 exchange and adsorption potential of low-permeable Carboniferous coals under deep subsurface conditions. CO_2 storage in (presently) unmineable coal seams in combination with coal-gas production appears to be an option, but still a geotechnical challenge.

Regulations and licensing

There is no general law governing permits for CO_2 storage in Germany. Storage is the subject of only two Research and Development projects, which are subject to existing mining laws and special legal conditions based on the laws of German unification. As mentioned previously, the CCS Directive will be transposed to national law and will require new laws to regulate permitting or monitoring of storage sites.

4.1.6 Poland

Geological and hydrogeological conditions

Mesozoic deep saline aquifers (Lower Triassic, Lower Jurassic and Lower Cretaceous) and associated Permian hydrocarbon reservoirs are prospective for underground CO_2 storage in the Polish Lowlands (**Figure 16.28**). The various structures in the area that are related to salt tectonics are sealed by thick impermeable rocks. Anticlinal traps of deep aquifers are located at Szczecin, Mogilno-Łódź, and the Warsaw

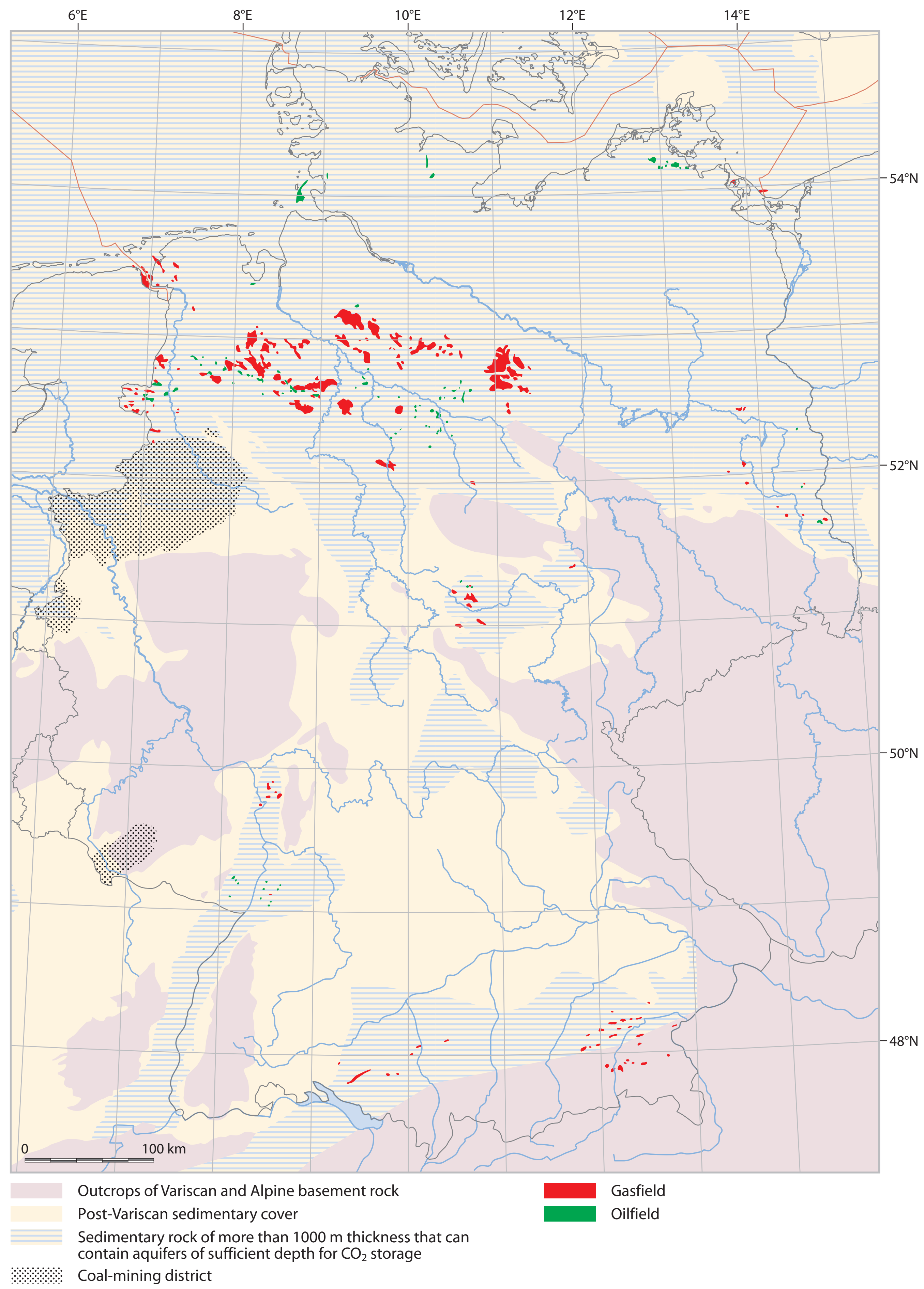


Figure 16.25 Regional distribution of storage options in Germany.

Trough and Kujawy Swell in Pomerania. There are Lower and Upper Permian hydrocarbon reservoirs in the Fore-Sudetic Region (Górecki, 1995; Karnkowski, 1999b; Tarkowski & Uliasz-Misiak, 2005, 2006).

Main geological areas for underground storage

Several oil and gasfields are potentially suitable for underground CO_2 storage (Tarkowski & Uliasz-Misiak, 2005). The largest are Barnówko-Mostno-Buszewo (BMB) and Cychry, with extractable resources of more than 5 Mt of oil and seven natural gasfields (BMB, Bogdaj-Uciechów, Brońsko, Kościan S, Radlin, Załęcze and Żuchlów) with extractable resources of more than 5 bcm of gas. The fields occur at depths of 1100 to 3700 m in western and north-west Poland and are sealed by Zechstein evaporites and Triassic and Jurassic sediments; they all have potential for CO_2 storage once the fields are depleted. The most suitable reservoirs for storage are deep aquifers in the Lower Triassic, Lower Jurassic and Lower Cretaceous successions (Tarkowski & Uliasz-Misiak, 2005, 2006) (**Table 16.13**), in addition to the Upper Triassic aquifers that are currently being considered. The 200 to 1600 m-thick Lower Triassic succession occurs at depths from several hundred metres to more than 5300 m in central Pomerania; the Kujawy Swell contains sandstones of the Baltik and Pomerania formations (Lower and Middle Buntsandstein Subgroups), which in central and northern Poland are regarded as good reservoirs. They are sealed by 100 to 200 m-thick Roethian silty and clastic-carbonate-evaporitic deposits (Upper Buntsandstein Subgroup) (Marek &

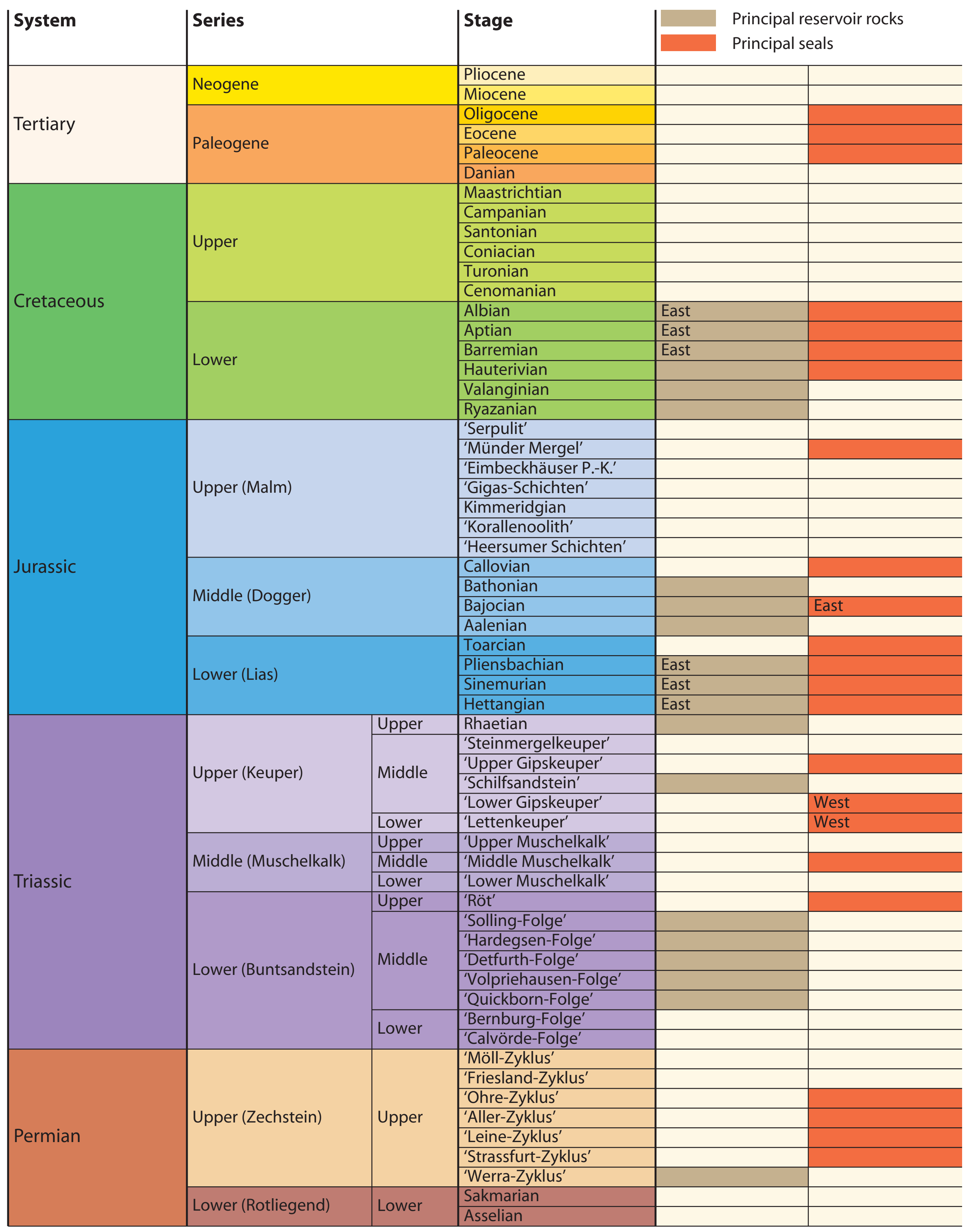


Figure 16.26 Stratigraphic overview including the most important aquifer and caprock formations in NE Germany.

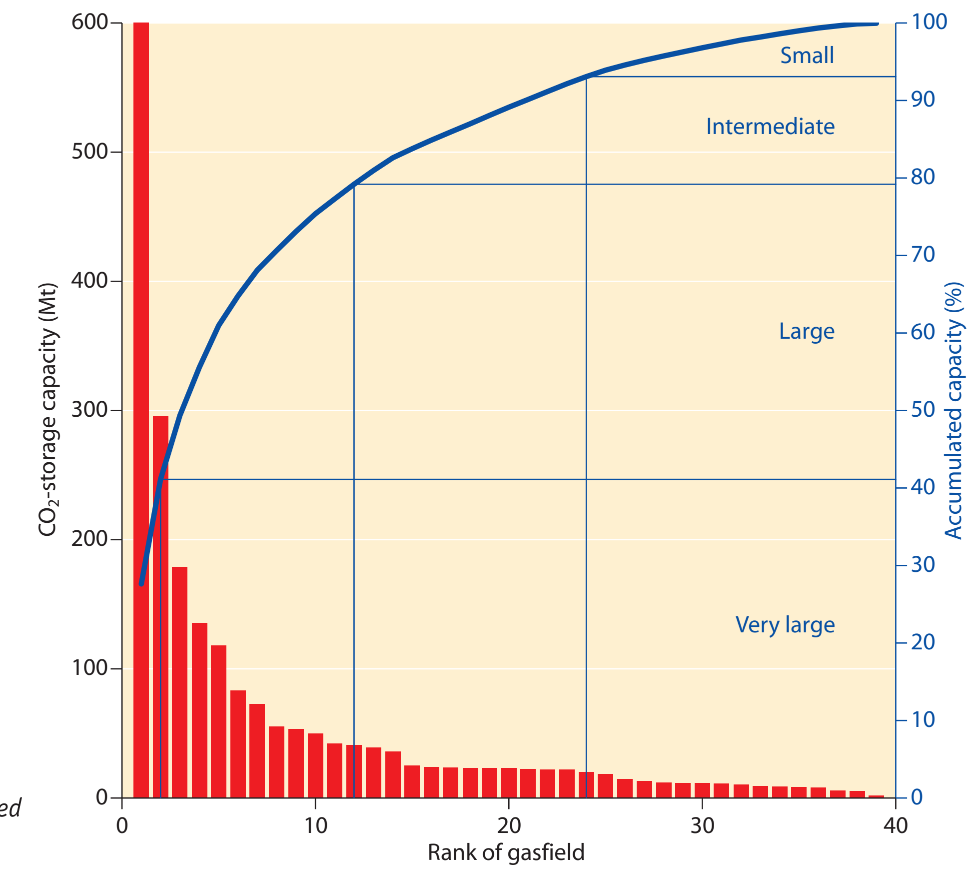
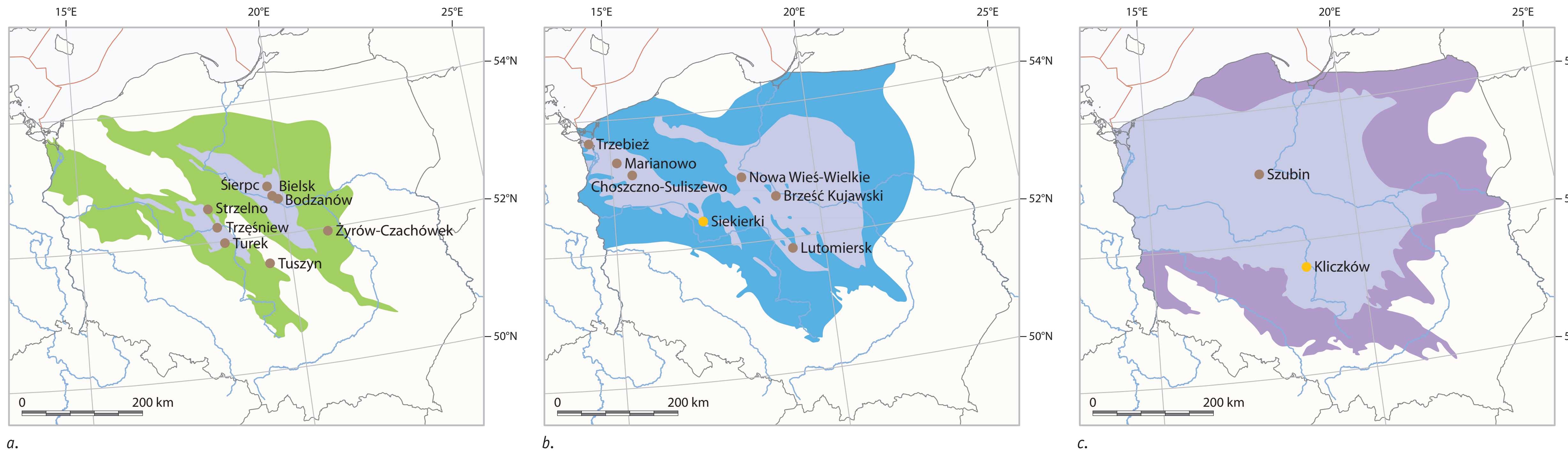


Figure 16.27 Storage capacity of gasfields in Germany. Estimated reserves are not included.



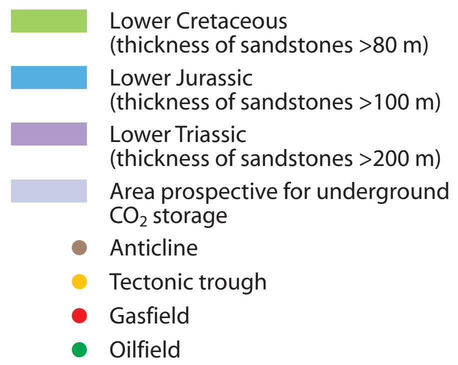


Figure 16.28 Prospective areas and geological structures selected for underground CO_2 storage in a. Lower Cretaceous; b. Lower Jurassic; c. Lower Triassic rocks. d. Geological units in Poland with hydrocarbon deposits selected for CO_2 storage.

Pajchlowa, 1997). The Lower Jurassic succession is 100 m thick near the basin margin and up to 800 to 1200 m in the Pomerania and Kujawy Swell area. The Pliensbachian and Toarcian sandstones at depths up to 3900 m are suitable for CO_2 storage. The Lower Jurassic succession is sealed by 100 to 160 m-thick upper Aalenian clays. The Lower Cretaceous (Barremian-Albian) sequence is up to 500 m thick and contains sandstones and carbonate-sand deposits separated by discontinuous, low to non-permeable, siltstones and mudstones and occurs at a depth of 2800 m in the Mogilno Trough. Within this succession, the sandstones of the Mogilno Formation (especially of the Kruszwica Member and locally of the Pagórczańskie Member) have the best reservoir properties. They are sealed by Upper Cretaceous limestones and chalks. Mesozoic aquifers provide most of the country's storage capacity; their huge potential is calculated in Gt. Tectonic structures in these aquifers have CO_2-storage capacities from 66 to 575 Mt and most are at least 100 Mt.

Economic importance: perspectives and problems

The European Union's Emission Trade System (ETS) may raise further interest in underground CO_2 storage. Poland's CO_2-storage capacity is one of the largest in Europe; as noted above, many geological structures have CO_2-storage capacities greater than 100 Mt (Tarkowski & Uliasz-Misiak, 2005). There is a possibility that an industrial CO_2-storage demonstration facility will be developed in central Poland. The subsurface CO_2-storage capacity in the Mesozoic aquifers of Poland is in the order of hundreds of times greater than that of hydrocarbon fields. In western Poland, acid gases (H_2S and CO_2) have been reinjected into the Borzęcin field since 1995.

Regulations and licensing

The Environmental Protection Law in Poland (POS, 2001) is not directly related to CO_2 storage. The Act on Waste (Ustawa o odpadach, 2001) does not classify CO_2 as waste material (Solecki, 2005). Neverthless, CO_2 injection into a natural-gas reservoir or aquifer is not legally permissible. CO_2 storage is regulated by the Act on Freedom of Economic Activity (Ustawa o swobodzie działalności gospodarczej, 2004) and therefore licensed under the Geological and Mining Law (PGG, 2004).

4.2 Gas storage

4.2.1 United Kingdom

Main geological areas for gas storage

Depleted oil and gasfields and salt-cavern storage facilities in the UK (**Figure 16.29**, **Table 16.14**) are mostly found onshore within the SPBA area to the west of the southern North Sea gas basin. Proven hydrocarbon reservoir rocks and important halite beds are Carboniferous to Triassic in age. Commercial hydrocarbons have been discovered in Silesian (Namurian and Westphalian) sandstone reservoirs onshore in the East Midlands, East Yorkshire and Lincolnshire and also offshore. In the East Midlands, these reservoir sandstones have porosities and permeabilities ranging from 9.5 to 25.6% and <1 to more than 1100 mD respectively (e.g. Ward et al., 2003; Hodge, 2003). The reservoirs occur in both structural and structural/ stratigraphic traps at depths of between about 400 and 2500 m. In the southern North Sea, commercial hydrocarbon accumulations are found in Namurian (porosities of 9.3 to 12.8%; permeabilities of 0.05 to 1000 mD) and Westphalian (porosities of 9.3 to 13%; permeabilities of 0.1 to 60 mD) reservoirs (Conway
& Valvatne, 2003b; O'Mara et al., 2003a, 2003b). These occur in structural and/or stratigraphic traps to the south of the Mid North Sea High at depths of about 3350 to 3750 m (e.g. O'Mara et al., 2003a, 2003b) and are sealed by shales.

The Lower Permian (Rotliegend) Leman Sandstone is the main sandstone reservoir in the southern North Sea and in East Yorkshire, with Permian Zechstein salts as seals in the majority of the fields. There is an additional reservoir at Caythorpe in the Permian Kirkham Abbey (Dolomite) Formation at depths between about 1750 to 2090 m and with an average porosity of 15%. The majority of the gasfields in Permian strata in the southern North Sea are tilted fault blocks sealed by the overyling Permian Zechstein salts. Within the UK sector of the southern North Sea, major diapiric (Zechstein Z2) salt structures are up to 2500 m thick, some with shallow buried crests (within 100 m of the sea bed: Cameron et al., 1992) and could be used for the construction of storage caverns.
The Triassic Sherwood Sandstone Group (Buntsandstein Group) is widespread across the UK sector of the southern North Sea and hosts a number of gasfields in broad anticlines formed above halokinetic

Table 16.13 Main features of the Polish aquifers suitable for CO_2 storage.

	Stratigraphy	Aquifer rock type	Reservoir type	Depth (m)	Total thickness (m)	Thickness of aquifer (m)	Porosity (%)	Permeability (mD)	Coefficient of permeability (average) (m/s)	Water mineralisation (g/dm^3)	Water temperature (°C)
Lower Cretaceous	Barremian-Albian	Sandstones	Fractured, porous	0-2800	Several to 650	Several to 350	10-45	2.25-4265.2; 20 (av.)	$2.13 \cdot 10^{-5}$; 1139.3 (av.)	<2-108.5	35-80
Lower Jurrasic	Hettangian, Sinemurian, Domerian and upper Toarsian	Sandstones	Fractured, porous	0-3900	Several to 1200	10-600	12-35	10-3800; 20 (av.)	$3.0 \cdot 10^{-5}$; 1100 (av.)	0.3-180	25-100
Lower Triassic	Bunter Sandstones	Sandstones	Fractured, porous	1500-5300	200-1300	25-300	2-30	0.1-761; 6.5 (av.)	$0.1 \cdot 10^{-6}$ to $2.5 \cdot 10^{-6}$; 70 (av.)	0.4-415	10-160

Table 16.14 Operational and planned UGS facilities in the UK. Data compiled in 2008.

Area	Site	Owner/operator	Storage capacity (mln m^3)	Number of caverns (Chalk & salt storage)	Approximate depth of storage (top-bottom if known) (m)	Comments
Operational facilities – depleted oil and gasfields						
Rough (offshore)	Southern North Sea	Centrica	c. 2832	Not available	c. 2743	Operational since 1985.
East Midlands	Hatfield Moors	Edinburgh Oil & Gas	122	Not available	c. 427	Operational since 2000.
Wessex-Weald Basin	Humbly Grove	Star Energy	280	Not available	c. 982	Operational since 2005.
Planned facilities – depleted oil and gasfields (in all cases development is subject to planning and other regulatory approvals)						
East Midlands	Welton	Star Energy	435	Not available	c. 1360	Planning application refused, applicant believed to be seeking approval under the Gas Act.
East Midlands	Saltfleetby	Wingas UK Ltd	600	Not available	c. 2234	Planning application submitted January 2006.
East Midlands	Hatfield West	Edinburgh Oil & Gas	Not available	Not available	c. 396	Planned – feasibility studies 2004-2005.
East Midlands	Gainsborough	Star Energy	227-240	Not available	c. 1375	Pre-planning stage.
East Yorkshire	Caythorpe	Scheme initiated by Warwick Energy Ltd, now Centrica	Up to 210	Not available	c. 1829	Planning consent refused 2006. Public Inquiry completed May 2007.
Wessex-Weald Basin	Albury – phase 1	Star Energy	160	Not available	c. 625	Pre-planning stage.
Wessex-Weald Basin	Albury – phase 2	Star Energy	Up to 715	Not available	c. 625	Pre-planning stage.
Wessex-Weald Basin	Bletchingley	Star Energy	Up to 900	Not available	c. 930-1143	Pre-planning stage.
Wessex-Weald Basin	Storrington	Star Energy	Not available	Not available	c. 1152	Pre-planning stage.
Southern North Sea	Esmond-Gordon (-Forbes) gasfields	EnCore and Star Energy	Esmond-Gordon up to 4,106	Not available	c.1402 (Esmond) and 1615 (Gordon)	Pre-planning stage.
Southern North Sea	Baird gasfield	Centrica and Perenco	c. 1700	Not available	c. 2440	Pre-planning stage. Centrica acquire 70% share in February 2009
East Irish Sea	Bains gasfield (110/03)	Centrica, Gaz de France & First Oil plc	Up to 566	Not available	c. 1250-1500?	Planning application approved June 2009.
Operational facilities – Chalk caverns						
North Lincolnshire	Killingholme	ConocoPhillips and Calor Gas	0.1 (liquid ≈60 000 t of LPG)	2	180-?210	Two mined caverns in Chalk c. 180 m below ground level; operational since 1985.
Operational facilities – salt caverns						
Cheshire Basin	Holford H-165	IneosChlor (formerly operated by NG (Transco)	0.175	1	350-420	Planning approval granted 1983. Ten year inspection completed 2006. One of number of abandoned brine cavities with ethylene & natural gas storage since 1984.
Cheshire Basin	Hole House Farm (Warmingham Brinefield)	EDF Trading	75	4	300-400	Planning permission granted 1995. 4 caverns, operation started in February 2001
East Yorkshire	Hornsea/Atwick	Scottish & Southern Energy	325	9	c. 1720-1820	Planning permission granted 1973, operating since 1979.
Teesside	Saltholme	SABIC (formerly IneosChlor/ Huntsman)	Up to 0.12-0.2	18 (plus 9 redundant)	350-390	Development in 1950s, storage started 1965-1982. 18 ex ICI caverns in operation. 1 'dry' cavity storing nitrogen; 17 'wet' storage cavities containing hydrocarbons ranging from hydrogen to crude oil; 9 redundant storage cavities; 75 redundant brine wells/cavities never used for storage; 5 in service brine wells.
Teesside	Saltholme	IneosChlor/Northern Gas Networks	0.08	4	340-370	4 ex ICI natural gas cavities. Development started 1959-1983, storage started 1959-1983. Now owned by IneosChlor & operated by NGN for natural gas.
Teesside	Wilton	SABIC (formerly IneosChlor/ Huntsman)	Up to 0.04	5 (plus 3 redundant)	650-680	Storage started from 1959 to 1983. 8 caverns leached, 5 operational cavities in total leached for storage purposes: 4 cavities storing ethylene, 1 cavity storing mixed C4's. 3 cavities redundant or never in service for storage.
Teesside	Wilton	SembCorp/BOC	Not available	2	650-680	2 ex ICI cavities – operational & storing nitrogen (for BOC Nitrogen).
Planned facilities – salt caverns (in all cases development is subject to planning and other regulatory approvals)						
Cheshire Basin	Byley/Holford (southern end of Holford Brinefield – Drakelow Lane area)	Scheme initiated by Scottish Power, sold to E.ON UK plc	160-170	8	630-730	Secretary of State reversed Public Inquiry decision. Under construction. Salt caverns to be leased from Ineos who own the salt and will construct caverns.
Cheshire Basin	Stublach (Holford Brinefield between Drakelow Lane and Lach Dennis)	Scheme initiated by Ineos Enterprises Ltd, now Gaz de France	540	28	c. 550-560	Planning permission granted late 2006. Under construction.
Cheshire Basin	King Street (Holford Brinefield)	King Street Energy (NPL Estates)	216	10	c. 400-500	Planning application submitted, Public Inquiry July 2009. Proposed construction of 9 cavities.
Cheshire Basin	Parkfield Farm (Warmingham Brinefield)	British Salt/EDFT	Not available – may be tied with Hill Top Farm	7	> c. 250	Planning approval granted late 2008-early 2009 to develop 7 new caverns.
Cheshire Basin	Hill Top Farm (Warmingham Brinefield)	British Salt/EDFT	c. 300	21	> c. 250	Planning approval granted late 2008-early 2009 to develop 10 former brine caverns and 11 new caverns.
East Yorkshire	Aldbrough South – Phase 1	Scottish & Southern Energy and Statoil	420	9	1800-1900	Planning permission granted 2000, 2 sites with 3 and 6 caverns. Under construction.
East Yorkshire	Aldbrough South– Phase 2	Scottish & Southern Energy and Statoil	420	9	1800-1900	Consent sought for extension to phase 1 development, with consent to increase storage capacity granted by East Riding of Yorkshire Council in May 2007.
East Yorkshire	North of Aldbrough (Whitehill)	E-ON UK plc	420	10	1800-1900	Geological feasibility studies carried out in 2006 on land to the north of Aldbrough. Planning application submitted to East Riding of Yorkshire Council, January 11th 2007. Anticipated first phase operational 2010, with completion 2013.
NW England	Preesall, Lancashire	Canatxx Gas Storage Ltd	c. 1200	20-24	245-510	Significant public objection to proposals. Public Inquiry completed (late 2005 – early 2006). Planning permission refused by Secretary of State (DCLG), October 2007. New planning application submitted February 2009; refused by Secretary of State (DCLG) October 2007.
East Yorkshire	North of Aldbrough (Whitehill Farm)	E-ON UK	420	10	c. 1800	Planning application submitted to East Riding of Yorkshire Council, January 2007.
Wessex-Weald Basin, Dorset	Isle of Portland	Portland Gas Ltd. (subsidiary Egdon Resources)	1000	14	2100-2300	Planning permission applied for in March 2007.
Larne, N Ireland	Larne Lough	Portland Gas NI Ltd (subsidiary Egdon Resources)	Not available	Not available	1680	Feasibility study stage, seismic acquisition in October 2007

Source: JESS and DTI 2006 reports, County Councils and company websites.

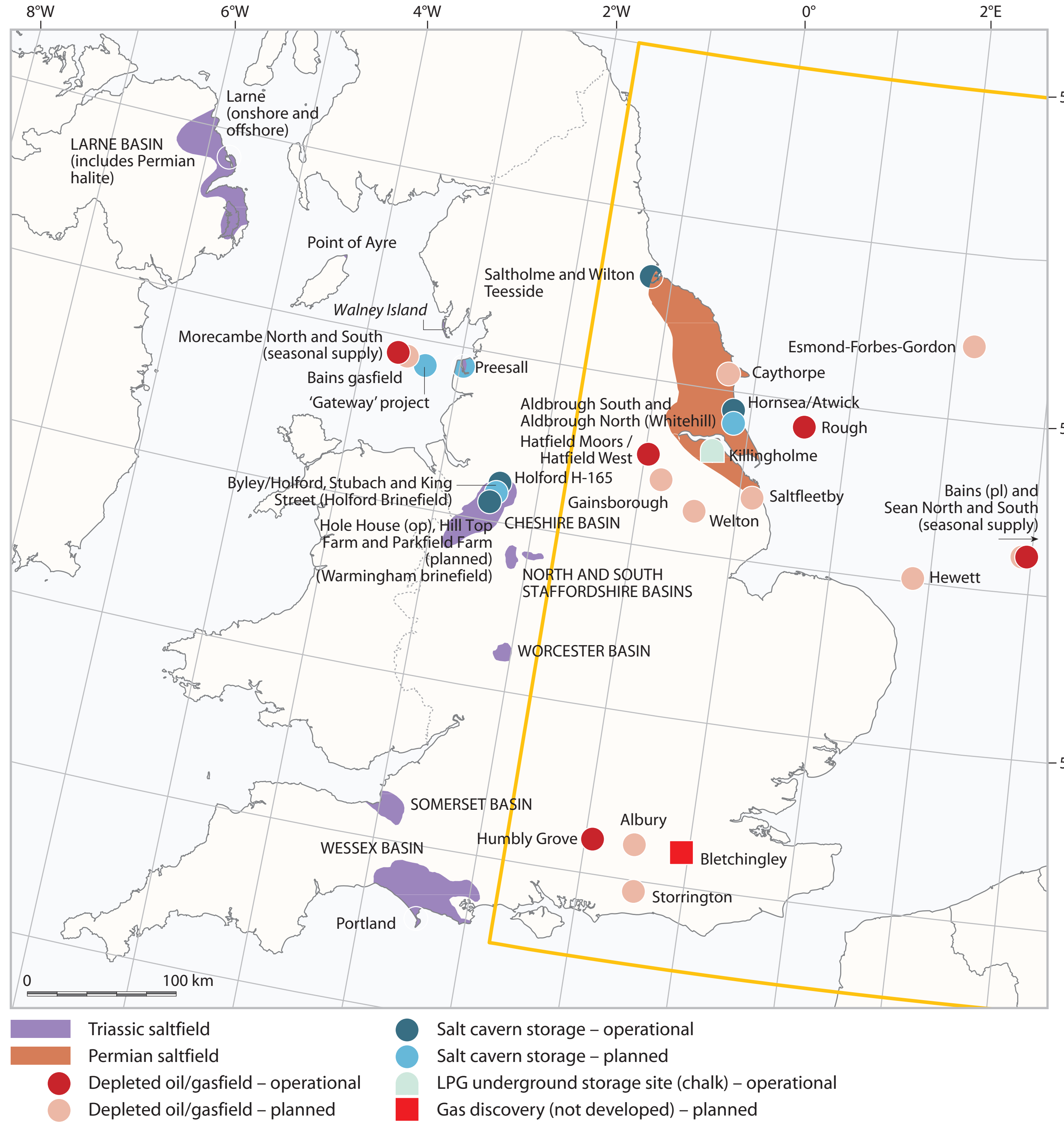


Figure 16.29 Operational and proposed UGS sites in the UK. The map includes town-gas storage sites investigated during the late 1950s and early 1960s and the Killingholme LPG chalk cavern storage site. Also shown are the existing and proposed offshore storage sites and gasfields developed as seasonal supply facilities (Morecambe and Sean fields).

structures in the Zechstein halites, including the Hewitt and the now depleted Forbes-Esmond-Gordon complex. Reservoirs in the latter occur at depths of about 2740 m, and have reservoir porosities and permeabilities of 15 to 25% and 10 to 10 000 mD respectively (Bifani, 1986; Ketter, 1991). The Triassic reservoirs are sealed by the overlying thick Triassic Mercia Mudstone Group sediments and were charged where the Zechstein seal was breached, most commonly due to the withdrawal of halite, permitting migration upwards into the Triassic rocks.

Economic importance: perspectives and problems

UGS facilities have been constructed in partly depleted oil and gasfields within the onshore SPBA area (**Figure 16.29**, **Table 16.14**). The Hatfield Moors storage facility is developed in the Oaks Rock Sandstone (Westphalian B) at a depth of about 426 m and started operations in 2000: porosities are 17.2 to 25.6% and permeabilities are 21 to 1100 mD (Ward et al., 2003). The Rough gasfield was converted to a gas-storage facility in 1985 (Stuart, 1991): the Rotliegend sandstone reservoir is at a depth of about 2750 m with an average reservoir thickness of 28.9 m, porosities of 6.3 to 22% and permeabilities of 0.05 to 1200 mD (Goodchild & Bryant, 1986; Stuart, 1991). Other gas-storage facilities in depleting hydrocarbon fields are planned at Welton and Saltfleetby (late Namurian to early Westphalian sandstones), Baird (southern North Sea: Rotliegend sandstones) and at Caythorpe (onshore: Permian sandstones).

In eastern England (**Figure 16.29**), gas is stored in large caverns leached in the Permian Fordon Evaporites (Zechstein Z2) at depths of 1400 to 1800 m near Hornsea on the East Yorkshire coast. Others are under construction or planned at Aldbrough and Whitehill directly to the south. To the north on Teesside (Billingham (Saltholme) and Wilton), about 30 salt storage caverns have been used for many years to store hydrocarbon products, nitrogen and hydrogen in the (Middle or Main) Boulby Halite Formation (Z3), which is up to 45 m thick and occurs at depths of about 300 m (Notholt & Highley, 1973). Leached cavern-storage facilities have been operational in the Triassic Northwich Halite beds of the Cheshire Basin at Holford since 1984 and at Hole House since 2001. Additional facilities in this basin are under construction at Byley and Stublach and are planned at King Street, Hill Top and Parkfield farms, and to the west in Triassic halites (Preesall Halite) in Lancashire (Preesall) and the East Irish Sea ('Gateway'). Large-purpose mined caverns (galleries) in the Upper Cretaceous Welton Chalk Formation have been used to store liquefied petroleum gas (LPG) since 1985 at depths of 180 to 190 m near Killingholme in North Lincolnshire (Geological Society, 1985; Trotter et al., 1985). The galleries were constructed partly by blasting and partly by roadheader, with product containment by groundwater (hydrostatic) pressure.

Regulations and licensing

The re-use of depleting oil and gasfields for gas storage is regarded as the most favourable storage option in the British (and European) Standard BS EN 1918-2:1998 (BSI, 1998a), with salt caverns also regarded favourably (BS EN 1918-3, 1998; BSI, 1998b). Non-regulatory issues relating to onshore UGS in partly depleted oil and gasfields are covered under existing petroleum legislation and licensing for exploration and production. The current legislative framework was not designed for the range of offshore-gas supply infrastructures anticipated and although they do not prohibit the development of infrastructure or such activities, they do give rise to legal uncertainties and unnecessary burdens to developers. New legislation would provide two determining authorities, the Crown Estate, who would issue geographically bound authorisations for the use of the sea bed or water column, and the Department of Energy and Climate Change (DECC), who would issue a Gas Storage Licence for offshore gas storage, or an LNG (liquified natural gas) unloading licence as appropriate. The Natural Gas Storage Licence would closely relate to the existing regime under the Petroleum Act 1998 and would be granted subject to the appropriate technical and environmental assessment(s). The UK Government is committed to bringing the requisite legislation forward as time and circumstances permit.

4.2.2 Belgium

Main geological areas for gas storage

The most prospective area for underground natural-gas storage is the Campine Basin (**Figure 16.20**), where the potential reservoirs are karstic or brecciated levels of the Carboniferous Limestone Group, coarse-grained sandstones in the Neeroeteren Formation and Buntsandstein Group and porous Cretaceous chalks. Potentially suitable structures in the western and north-eastern parts of the Campine Basin need further investigation. The reservoir at Loenhout (**Figure 16.20**), the only UGS facility in Belgium, is formed by karst and brecciated horizons within the Carboniferous Limestone Group. The reservoir is at hydrostatic pressure and sealed by Namurian claystones. The top of the storage zone occurs at a depth of 1000 m.

Economic importance: perspectives and problems

The Loenhout site is a UGS facility for high-caloric gas. The site started operations in 1985, since when the working gas volume has been increased up to its current capacity of 580 mln m^3(n) The present total injection capacity of the facility is 250 000 m^3(n)/h. Total emission capacity reaches 500 000 m^3(n)/h. It is planned to increase the capacity of the facility in the coming years to about 650 mln m^3(n) working gas, a total injection capacity of 350 000 m^3(n)/h, and a total emission capacity of 625 000 m^3(n)/h.

Regulations and licensing

UGS is a federal matter. Exploration and site development is regulated by the law covering the exploration and exploitation of natural reservoirs for UGS of 18 July 1975. Operations are regulated by the Commission for the Regulation of Electricity and Gas. Operators have to comply with regional safety and environmental regulations during exploitation of the site.

4.2.3 The Netherlands

Main geological areas for gas storage

In the Netherlands, the preference is to store gas in (partially) depleted gasfields as these structures have trapped gas for millions of years and so can be considered to be gas-tight. Theoretically, injection into aquifers would also be an option provided that the aquifer has a suitable structure and is overlain by a sealing caprock. The main reservoir rocks in the Netherlands are the Slochteren Formation (upper Rotliegend Group), Zechstein Group carbonate and dolomite sequences, Main Buntsandstein Formation (Lower Germanic Triassic Group), and sandstones in the Vlieland Sandstone Formation (Lower Cretaceous Rijnland Group). The rocks are widespread and range from about 50 m up to several hundred metres thick (**Figure 16.30**). Two different gas-storage functions are distinguished, the smaller peak shavers and the larger seasonal storages (or 'volume shifters'). An example of the former is Alkmaar and of the latter are Norg (lo-caloric gas) and Grijpskerk (hi-caloric gas) (**Figure 16.31**). The disadvantage of the larger gasfields is that their volumes are too large to meet the design criteria of peak shavers. The reservoir is porous, which usually implies significant internal flow resistance. These problems do not occur when gas is stored in salt caverns. There are Zechstein salts in the northern Netherlands, where several salt diapirs and a few salt walls may be suitable for UGS.

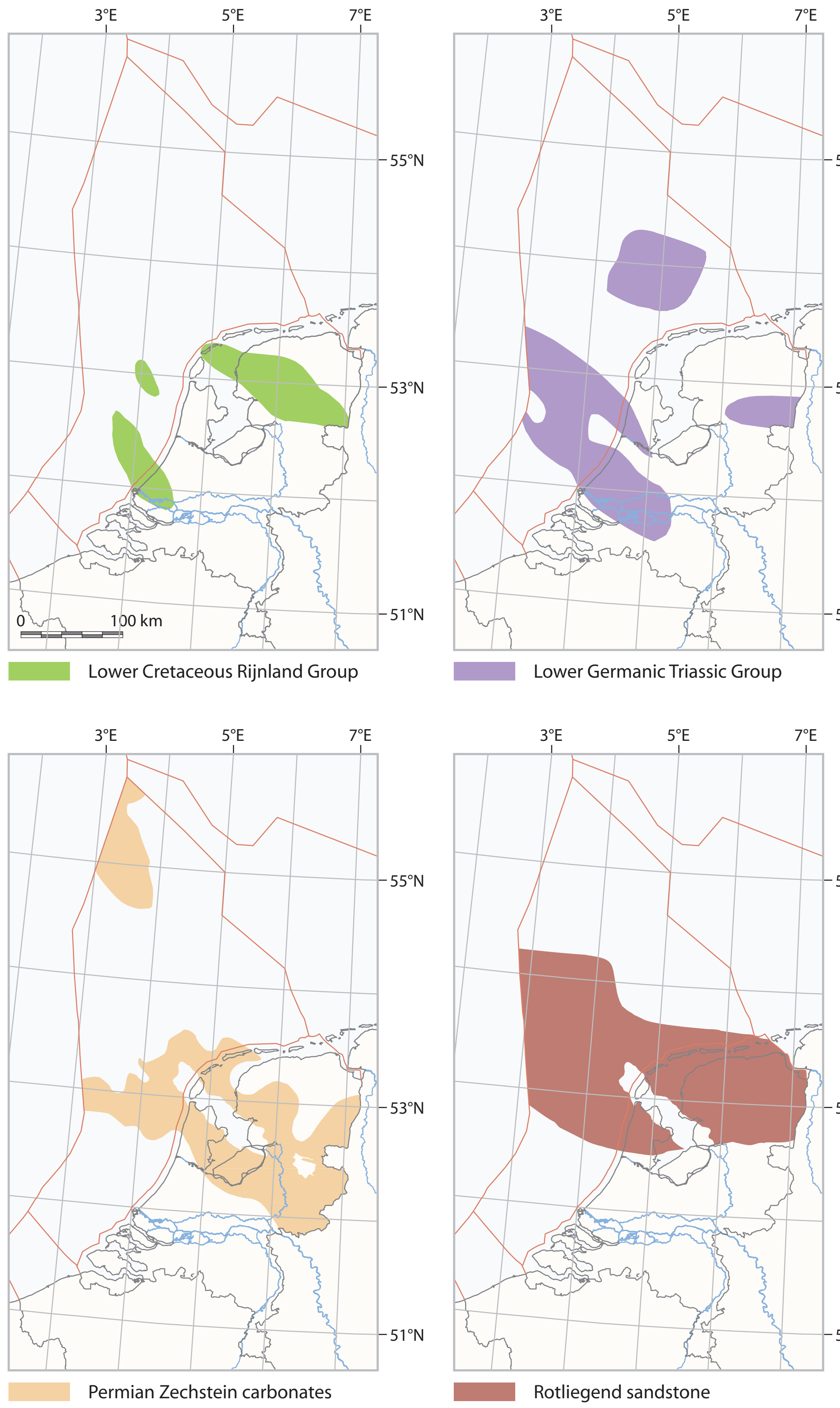


Figure 16.30 Distribution of the main reservoir rock in the Netherlands.

Economic importance: perspectives and problems

The giant Groningen field has an estimated ultimate recovery of 2700 bcm and has traditionally been used as the main 'swing producer' (i.e. to balance seasonal, daily or hourly fluctuations in demand). The field has already produced more than half of its initial reserves and consequently the reservoir pressure can no longer guarantee the supply-demand balance under all circumstances. Three smaller gasfields at Norg, Grijpskerk and Alkmaar (**Table 16.15** & **Figure 16.31**) have therefore been converted to UGS facilities as described above. These fields can deliver a maximum gas rate of about 140 bcm/d and a cycle (i.e. injection and reproduction) of about bcm/year. A new UGS facility is planned in the depleted gasfields at Bergermeer and Waalwijk. Salt caverns created by circulating freshwater around a well bore to dissolve the salt (Geluk et al., 2007b) are only suitable for storing relatively small volumes of gas at limited depths; a practical upper limit for the volume is about 500 000 m^3. Storage capacity can be increased by constructing multiple caverns a few hundred metres apart and linking them through surface facilities. The development of such salt caverns for gas storage is planned near Zuidwending in the province of Groningen (**Figure 16.31**) and at Epe (in Germany, near the Dutch border) (**Figure 16.33**).

Regulations and licensing

The Mining Act (MA), the Environmental Management Act (EMA) and the Spatial Planning Act (SPA) provide the main legal framework for the application of gas storage. The Ministry of Economic Affairs is the responsible authority for the MA; the EMA and SPA are under the authority of the Ministry of the Environment. The storage of gas (both temporary and permanent) in the subsurface is governed by the Mining Law (Mijnbouwwet) of January 1st, 2003. It does not stipulate the commercial terms and conditions for undertaking storage operations as these are imposed by the relevant EU Directives and by the Dutch Gas Law. Several commercial details are the subject of ongoing discussions (e.g. the tariff structure for flexibility services such as provided by UGS, and the issue of Third Party Access).

Table 16.16 provides an overview of all legal documents that are directly, or indirectly associated with gas storage, including the accompanying permits and responsible authorities.

Table 16.15 Characteristics of the three UGS facilities currently operational in the Netherlands (see Figure 16.31 for locations.

UGS facility	Norg	Grijpskerk	Alkmaar
Reservoir formation	Rotliegend	Rotliegend	Zechstein
Depth of reservoir (m; approximate)	3 000	3 200	2 000
Maximum daily withdrawal (10^6 m^3/d)	51	56	36
Minimum daily withdrawal (10^6 m^3/d)	4	4	2.4
Maximum daily injection (10^6 m^3/d)	12	12	3.6
Minimum daily injection (10^6 m^3/d)	10	10	?
Total gas volume (10^6 m^3/d)	28 000	13 100	3 600
Working gas volume (10^6 m^3)	3 000	15 00	500
Cushion gas volume (10^6 m^3)	25 000	11 600	3 100
Ratio working/total gas (%)	10.7	11.5	13.9
Duration of withdrawal (days)	69	29	14

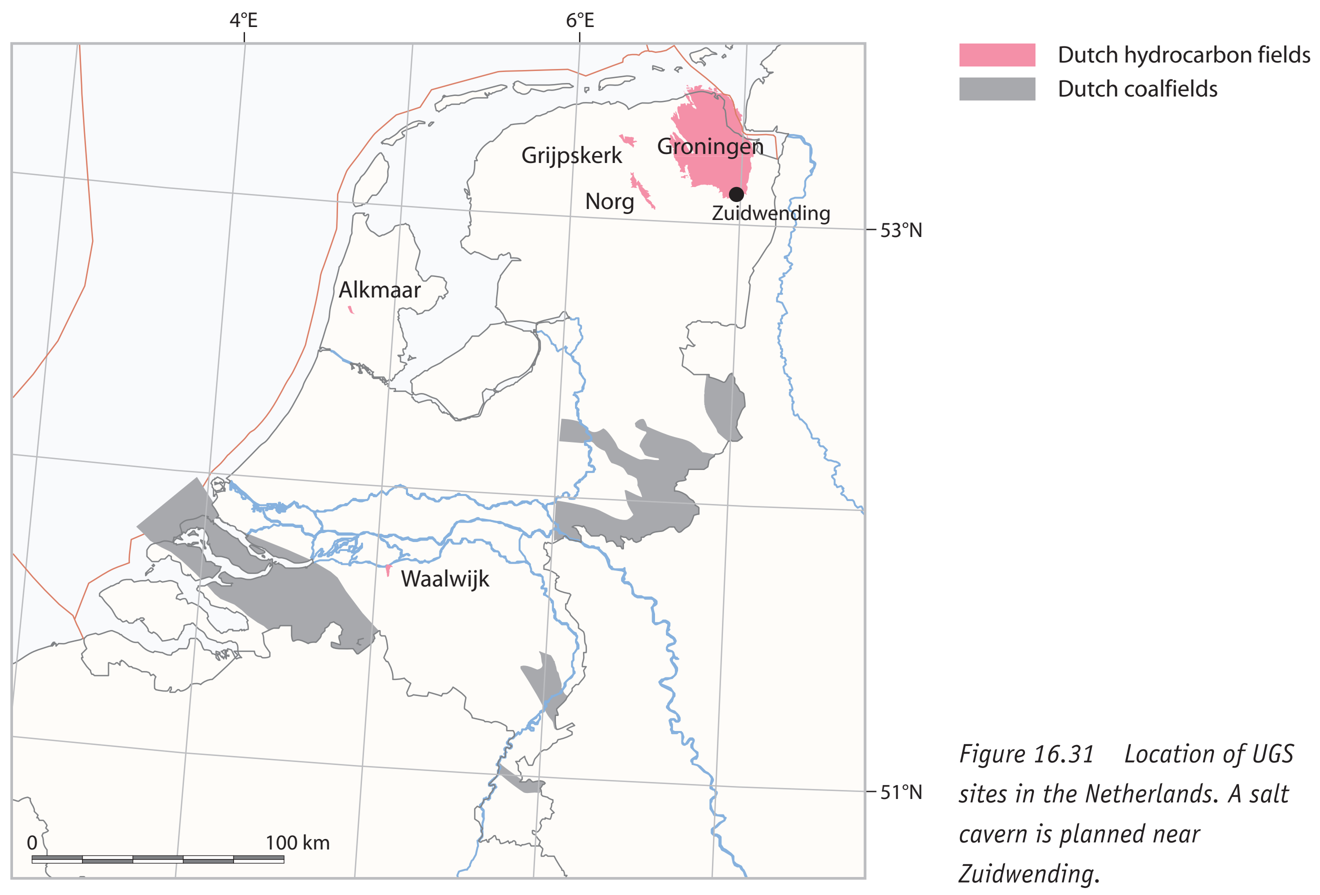


Figure 16.31 Location of UGS sites in the Netherlands. A salt cavern is planned near Zuidwending.

Table 16.16 Overview of all legal documents that are directly or indirectly associated with gas-storage activity in the Netherlands, including the accompanying permits and responsible authorities.

Permit	Legal framework	Responsible authority
Storage permit	Mining Act	Ministry of Economic Affairs
Environmental permit surface installation	Environmental Management Act	Ministry of Economic Affairs
Environmental permit subsurface[1]	Environmental Management Act	Provincial Executive[2]
(Change in) spatial plan	Spatial Planning Act	Municipalities
Building permit	Building Act	Municipalities
Construction permit	Spatial Planning Act	Municipalities
'Ontgrondingsvergunning'	'Ontgrondingenwet'	Provincial Executive
'Onttrekkingsvergunning/melding'	Groundwater Act	Provincial Executive
Discharge permit	Contamination surface water Act	Water Board
Nature Protection permit	Nature Protection Act	Provincial Executive
Archaeological Research	Monument Act	Provincial Executive
Exemption	Vegetation and animal life Act	Ministry of Agriculture, Nature and Fishery
Exemption Provinciale Omgevingsverordening	Provincial environmental Regulation	Provincial Executive

1 The future responsible authority for the environmental permits is currently under debate.
2 The Ministry of Economic Affairs is responsible for waste originating from mining activities.

4.2.4 Denmark

Main geological areas for gas storage

The deep saline aquifers mapped for geothermal exploitation (Section 3.4) may also be used for CO_2 and natural-gas storage, provided a suitable closure and seal exists (**Figure 16.22**). The mapping of suitable structures for natural-gas storage performed in the 1980s, and more recently on CO_2 storage, is summarised in **Table 16.12** and **Figures 16.16** & **16.17** (Christensen & Holloway, 2003; Larsen et al., 2003). Only one anticlinal trap is currently used to store natural gas at Stenlille (**Figure 16.32**). The injected gas replaces saline water in the sandstones of the Upper Triassic Gassum Formation at 1500 to 1600 m depth. The reservoir is sealed by the 300 m-thick Lower Jurassic Fjerritslev Formation clay sequence (**Figure 16.17**). Gasfields in the Danish North Sea may be suitable for underground storage of natural gas as they become depleted (**Figure 16.32**). The use of depleted oil and gas reservoirs would have been a preferred option for natural-gas storage, but no onshore commercial hydrocarbon accumulations had been found at the time that the transmission network was set up in the 1980s. However, in 1981, the gas reservoir in the Buntsandstein Group of the Tønder structure (**Figure 16.22**), which held a large volume of almost pure nitrogen, was concluded to be suitable for underground natural-gas storage (**Table 16.12**; Øbro, 1989; Christensen & Holloway, 2003). The Tønder gas reservoir has not yet been used for natural-gas storage. Deep aquifers and salt domes offer further possibilities for UGS in Denmark. Zechstein salt domes that could be used for natural-gas storage are found in the Danish Basin in the Jylland area (Fabricius, 1984). One UGS facility has been established in the salt dome of Ll. Torup, where seven caverns have been leached.

Economic importance: perspectives and problems

The present storage capacity in Ll. Torup is 0.7 billion Nm^3, equivalent to 10% of the yearly consumption of natural gas in Denmark. The estimated gas-storage capacity at Stenlille is about 3 billion Nm^3. UGS facilities have to be monitored carefully for safety and environmental protection.

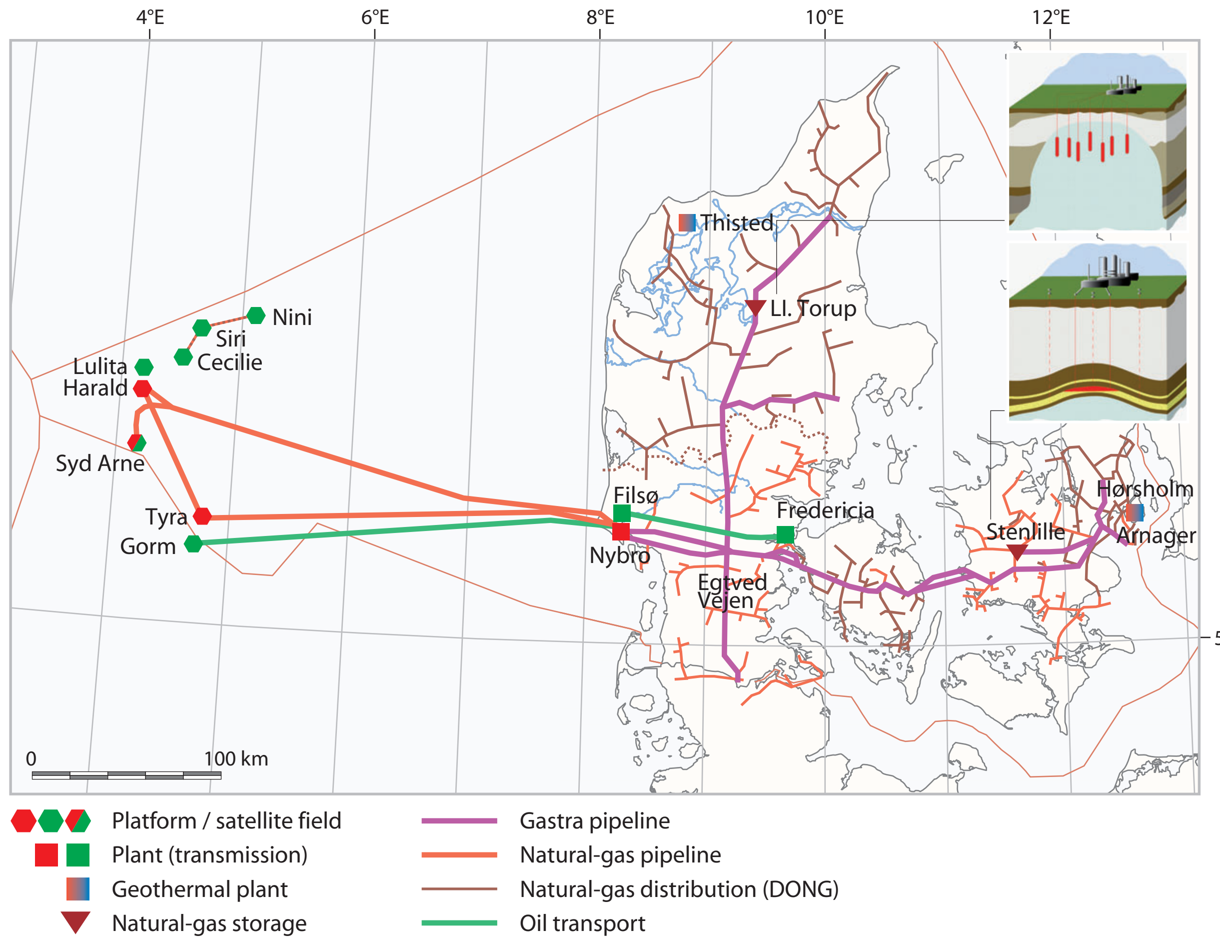


Figure 16.32 The natural-gas distribution network in Denmark. Gas from the oil and gasfields in the North Sea is transported via pipelines to consumers and to the two UGS facilities in Ll. Torup (salt cavern) and Stenlille (deep sandstone aquifer). The two facilities were established in the 1980s to ensure a steady supply of gas to consumers.

4.2.5 Germany

Main geological areas for gas storage

Germany has ideal geological conditions for UGS. There are numerous porous rocks in aquifers and depleted hydrocarbon fields in the major sedimentary basins such as the North German Basin, Thüringian Basin, Upper Rhine Valley and the Molasse Basin. The major prospective horizons in northern Germany are the Triassic sandstones (e.g. Buntsandstein Group) and dolomites in the Zechstein carbonate units. Tertiary sandstones and chalks have most potential for gas storage in southern Germany. The reservoirs are found mainly in anticlines and tectonic/stratigraphic traps, and the seals are either tight claystones or salt layers. The depths of the reservoirs range from several hundreds of metres up to 2900 m. Gas storage in salt caverns is limited to northern Germany where salt domes or pillows commonly occur within the Zechstein reservoirs. In one instance, the Rotliegend sandstone series may also serve as a gas-storage facility. The highest operational pressures are achieved in the Buntsandstein Group succession, which is sealed by Triassic salt beds (Röt Formation). All locations of UGS storage facilities, salt caverns, mines and depleted hydrocarbon reservoirs are shown on **Figure 16.33**.

Economic importance: perspectives and problems

Natural gas is the second most important energy source after oil (36%) and provides about 23% of Germany's total primary energy supply (www.lbeg.niedersachsen.de). Gas storage in Germany dates back to 1949 when a pilot project to test air injection was carried out at Gifhorn in Lower Saxony. Forty-four UGS facilities are now operated by some 20 companies and provide a total of 19.1 bcm of installed working gas volume (**Table 16.17**). The development of working gas volume since the beginning of UGS operations in Germany is still increasing (**Figure 16.34**); about 19% of the total gas consumption is available in UGS facilities. Several re-leaching projects in existing salt caverns are planned to increase their geometrical storage volume (e.g. the salt cavern at Huntorf K6 was planned to store a geometrical volume of 750 000 m^3

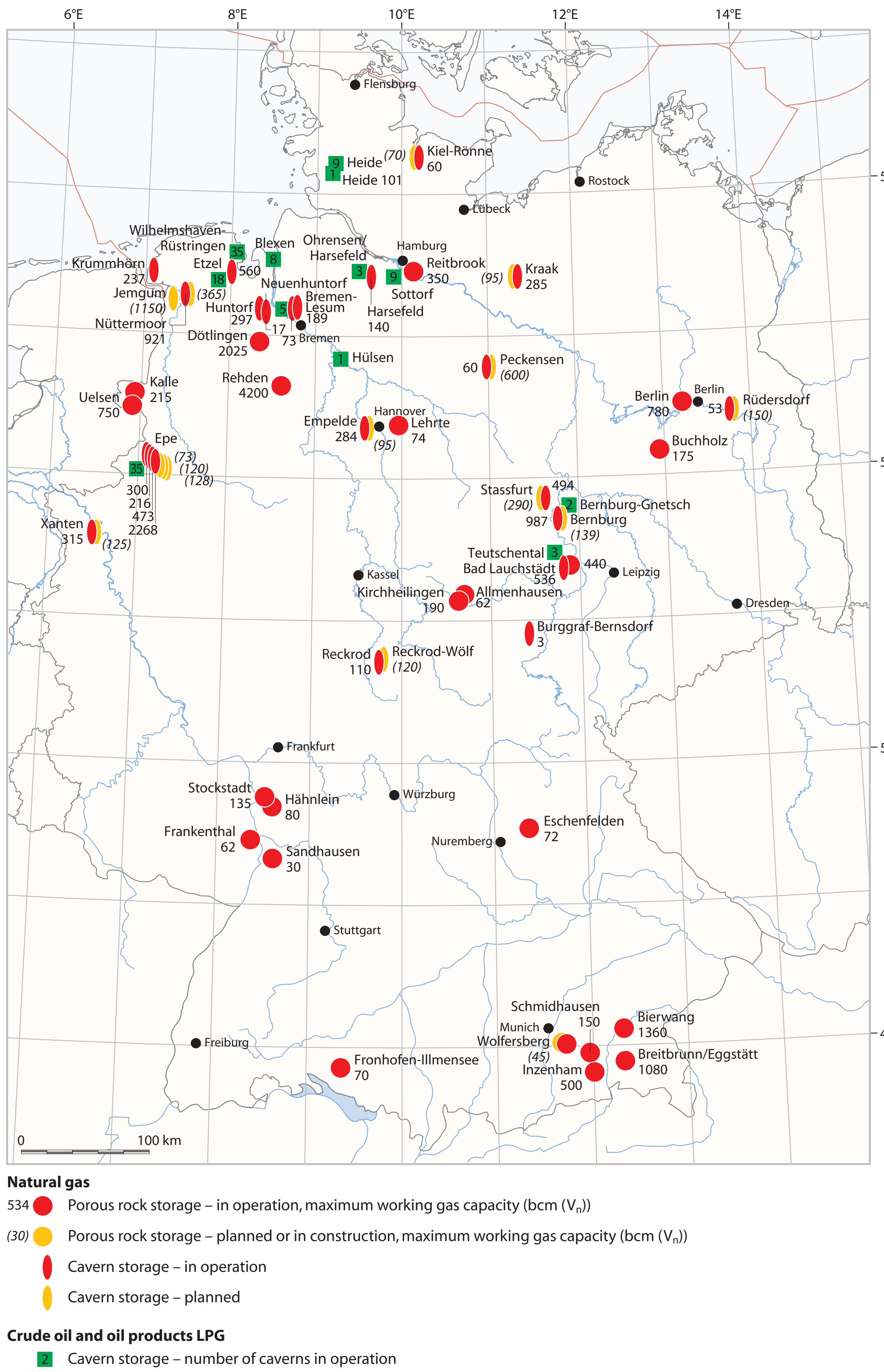


Figure 16.33 Locations of UGS in Germany.

but could be enlarged to 1.1 bcm). The major projects will be concentrated in salt caverns in northern Germany (Epe, Etzel, and Jemgum) and aquifers in eastern Germany. New types of low-pressure mud systems are used to prevent formation damage in depleted reservoirs with low reservoir pressure. Future UGS facilities in Germany will be affected by 'North Stream', the planned gas pipeline through the Baltic Sea.

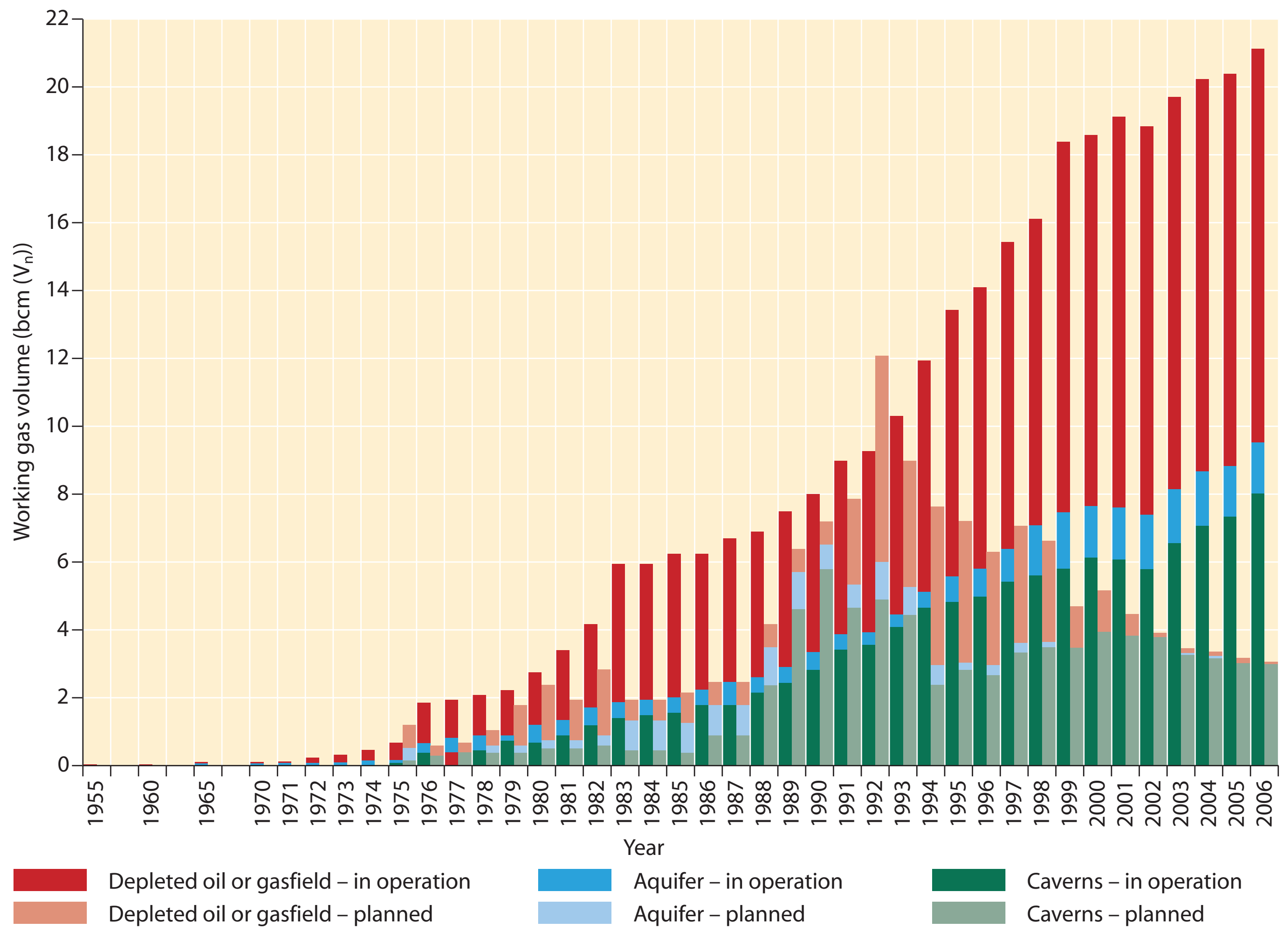


Figure 16.34 Working gas volumes in UGS facilities in Germany.

Table 16.17 UGS in Germany. Data from 31st December 2006.

	Unit	Porous rock storage	Cavern storage	Total
Working gas volume (WGV) in operation	bcm (V_n)	12.4	6.7	19.1
WGV after upgrading•		13.1	8.0	21.1
Plateau-Production-Rate	bcm (V_n)/d	192.6	270.2	462.8
Theoretical time of availability of the WGV[1]	days	64	25	41
Number of UGS in operation		23	21	44
WGV planned or in construction•	bcm (V_n)	0.05	3.0	3.1
Number of UGS planned or in construction		1	14	15
Sum WGV (• + •)	bcm (V_n)	13.2	11.0	24.2

1 Calculated (theoretical) value.

Regulations and licensing

Applications for permission to store gas ('Betriebsplanantrag') are granted by the Mining Authorities of the Federal States, independent of existing exploration or production permits. The applications and the operation of UGS are subject to regulations according to the Mining Law ('Bundesberggesetz'). All subsurface (geological) data acquired are submitted to the geological surveying authorities in accordance with the Mineral Law ('Lagerstättengesetz'). There is no specific tax on exploration and operational activity at UGS sites.

4.2.6 Poland

Main geological areas for gas storage

Gas may be stored in gas or oil reservoirs that are exhausted, partly exploited or closed-in, and in salt caverns created within salt deposits. The caverns are in both salt domes and stratiform salt deposits (Brańka et al., 1978). There are numerous oil and gasfields within Rotliegend sandstones at depths between 1200 and 3484 m in the Fore-Sudetic Monocline between 2843 to 3856 m in Pomerania (**Table 16.18**); Upper Permian carbonates (Zechstein Limestone and Main Dolomite units) at depths of 1000 to 2986 m in south-western and central Poland and 2250 to 3805 m in Pomerania. There are also a few oil and gasfields in Upper Carboniferous sandstones (at depths of 2770 to 3164 m and at 2985 to 3220 m) and in the Middle Cambrian succession of eastern Pomerania (at depths of 2695 to 2740 m) (Karnkowski, 1999c). Gasfields with UGS potential have been identified at five closed-in and almost exhausted gasfields in south-western Poland (Reinisch, 2000) (**Figure 16.35**). These are Wierzchowice (with more than 4 × 10^{12} m^3 total free volume in gas-exhausted fields (Reinisch, 2000; **Figures 16.35** & **16.36**), Brzostowo (in sandstones and carbonates at depth of 1323 to 1452 m) and at Załęcze, Żuchlów and Wilków (sandstones at 1249 to 1520 m depth; **Table 16.19**). The sandstones and carbonates have a total pore volume of about 28.5 bcm, temperatures of 14 to 32°C, and porosities of 7.6 to 17.4% and 3.6 to 13.9% and permeabilities of 1.6 to 1000 mD and 0.5 to 11.4 mD respectively. Salt caverns could be leached within salt domes and diapirs of the Zechstein evaporites (oriented in a north-west–south-east direction throughout Poland) and in the Zechstein stratiform salt deposits at Gdańsk Bay and in south-west Poland (**Figure 16.37**) with thicknesses of more than 200 m. UGS is planned (Reinisch, 2000) in seven sequences containing groundwater in central and north-western Poland (**Figure 16.35**, **Table 16.20**). The Chabowo aquifer occurs in Lower Jurassic and Lower Cretaceous sandstones at depths of 88 to 670 m and has porosities of 18 to 30% and permeabilities of 10 to 1330 mD. There are six other aquifers within Lower Cretaceous sandstones (with porosities of 11 to 30% and permeabilities of 10 to 9848 mD) at depths of 740 to 1200 m near Warsaw and 735 to 900 m near Łódź.

Table 16.18 Age and depth of oil and gas deposits in the Polish Permian Basin (after Karnkowski, 1993, 1999b; Przeniosło, 2005).

Age of hydrocarbon reservoir rocks	Deposit lithology/depth (m)				Number of gas deposits active/ reserved/ closed	Number of oil deposits active/ reserved/ closed
	SW & Central Poland		Northern Poland			
	Gas deposits (125)	Oil deposits (26)	Gas deposits (8)	Oil deposits (13)		
Mid Cambrian	-	-	-	Sandstones/ 2695-2740	84/41/8	29/4/6
Late Carboniferous	Sandstones/ 2770-3164	-	Sandstones/ 2985-3220	- -		
Early Permian (Rotliegend)	Sandstones/ 1200-3484	-	Sandstones/ 2843-3856	-		
Late Permian (Zechstein; Ca1, Ca2)	Carbonates/ 1470-2420 (mainly Ca2, Ca1)	Carbonates/ 1000-2986 (Ca2)	Carbonates/ 2842-2930 (Ca2)	Carbonates/ 2250-3805 (Ca2)		

(125) Number of deposits   Ca1 Zechstein Limestone   Ca2 Main Dolomite

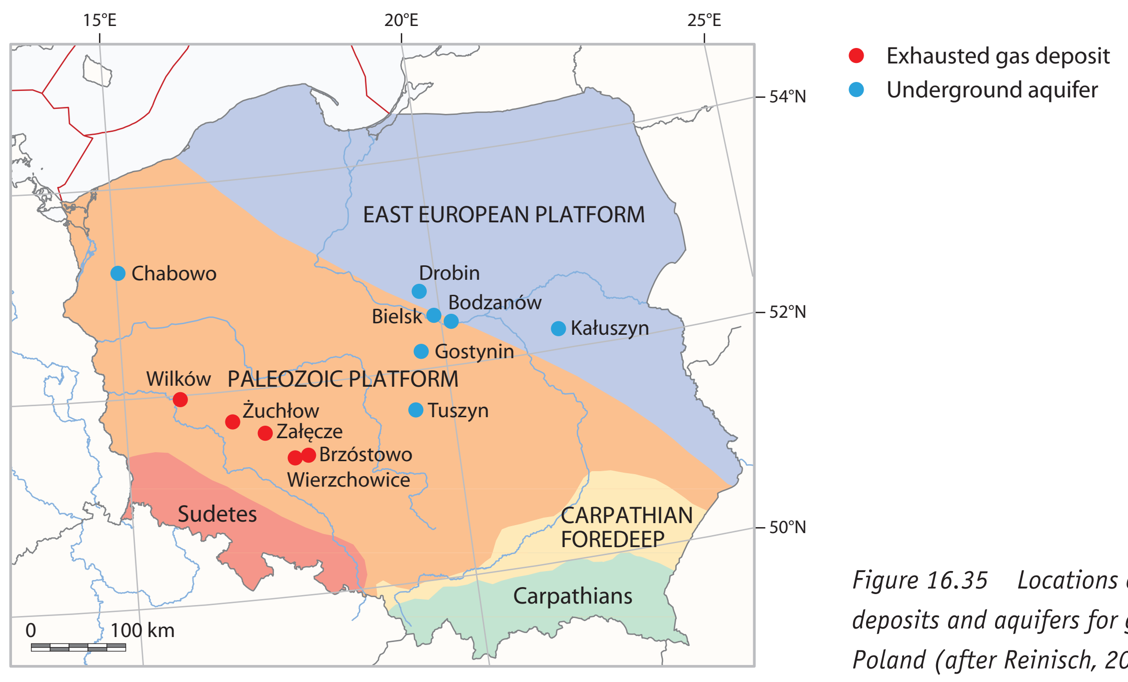


Figure 16.35 Locations of selected gas deposits and aquifers for gas storage in Poland (after Reinisch, 2000).

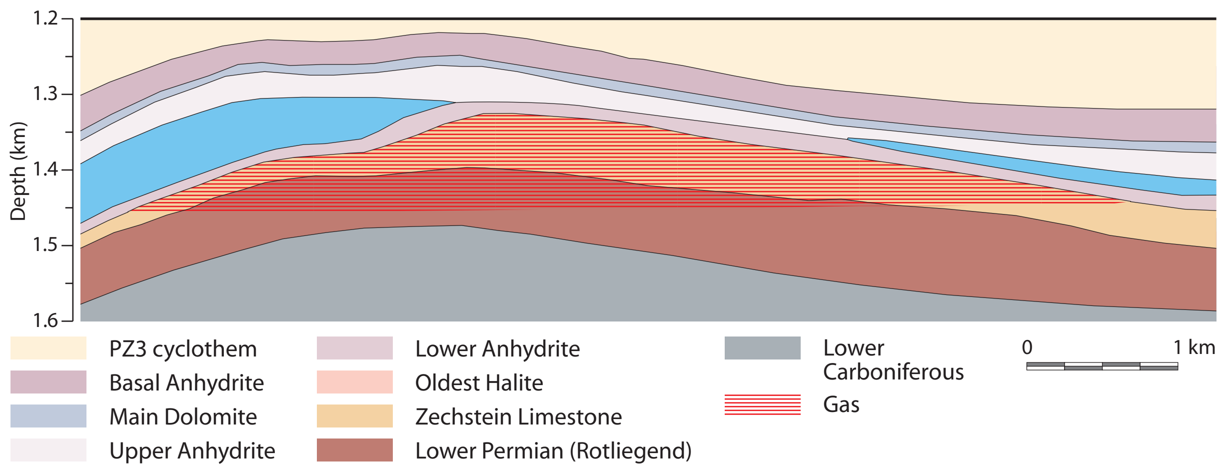


Figure 16.36 Cross-section of the Wierzchowice gas deposit adapted for gas storage (after Karnkowski, 1993). See Figure 16.35 for location of the gas deposit.

Table 16.19 Characteristics of selected gas deposits planned for UGS in Poland (after Karnkowski, 1993, 1999b; Reinisch, 2000). See Figure 16.35 for locations of deposits.

Deposit name	Deposit depth/ thickness (m)	Type and age of deposit rocks	Area (km^2)	Porosity (%)/ permeability (mD)	Pressure (mPa)/ temperature (°C)	Volume of gas storage: actual/ planned (mln m^3)
Wierzchowice	1323.5-1452/ 128.5	Sandstones (Early Permian, Rotliegend) & carbonates (Late Permian, Zechstein Limestone)	23	10.73/-; 3.6-13.93/0.7-11.4	16.5/47	600/4300
Brzostowo	1400-1450/50	Sandstones (Early Permian, Rotliegend) & carbonates (Late Permian, Zechstein Limestone)	16.5	7.6/1.5783; 5.6/0.4976-8.36	16.36/56	0/700
Załęcze	1249-1354/35	Sandstones (Early Permian, Rotliegend)	32	17.4/200	15.1/47	0/9500
Żuchlów	1275-1345/70	Sandstones (Early Permian, Rotliegend)	25	15/1000	14.66/49	0/12500
Wilków	1475-1520/45	Sandstones (Early Permian, Rotliegend)	c. 14	-	16.32/53	0/1500

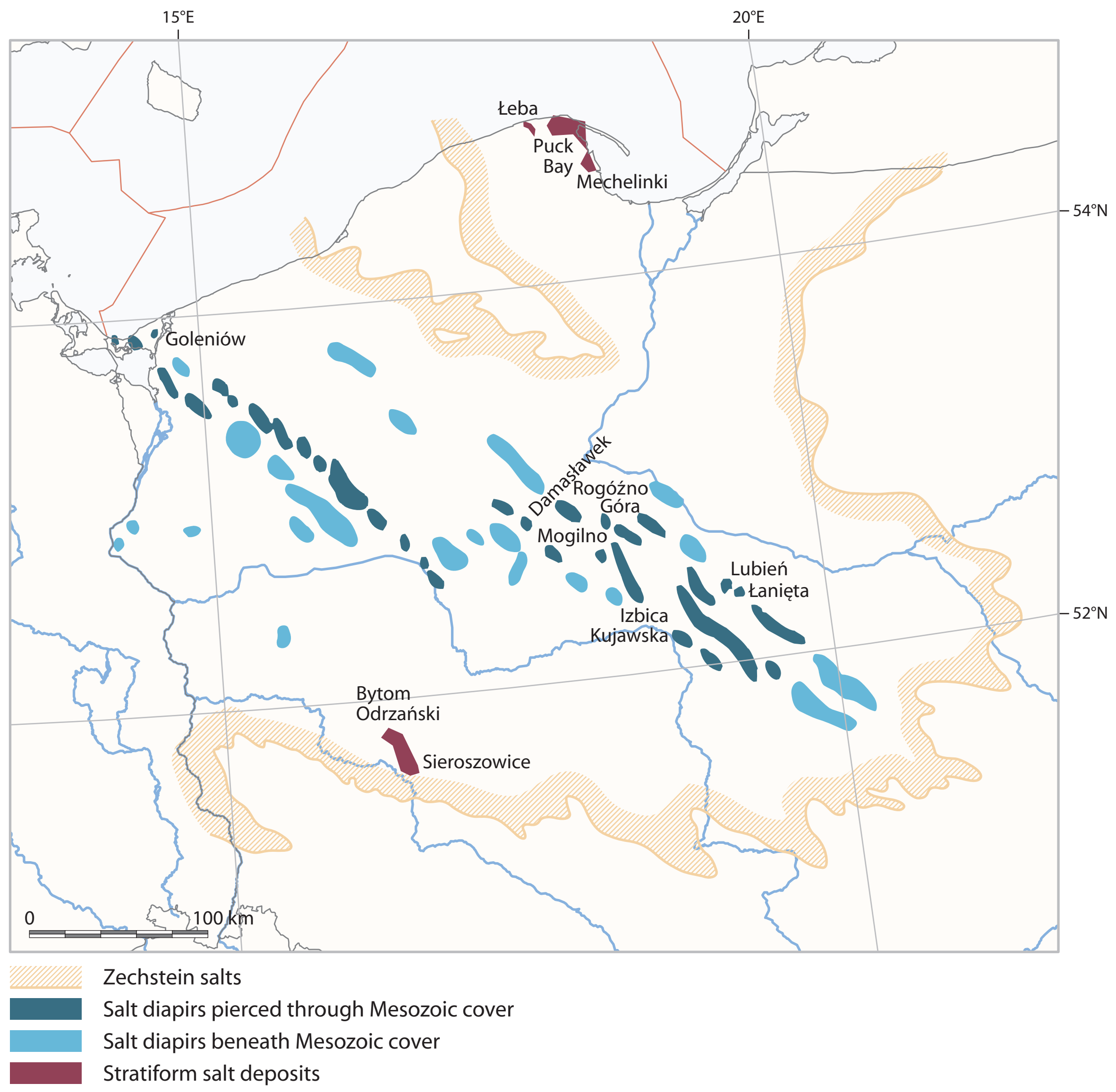


Figure 16.37 Location of selected Upper Permian salt diapirs and stratiform salt deposits suitable for gas storage in Poland (after Karnkowski & Czapowski, 2007).

Economic importance: perspectives and problems

Poland has limited gas resources: there are 231 gasfields with total resources estimated at 154 bcm; 183 fields have produced about 5.2 bcm providing 43.2% of the national demand in 2004. More than 60% of the gasfields are now exhausted (Przeniosło, 2005). The partly exhausted Wierzchowice field was transformed in 1995 into a UGS facility with a potential storage volume of about 4.3 bcm (Reinisch, 2000). There are three salt deposits in the stratiform salt deposits of northern Poland (**Figure 16.37**), the Łeba, Puck Bay and Mechelinki deposits, which occupy a total area of 157 km^2 and have estimated resources of 21 billion Mg of salt. These deposits include a salt seam up to 225.5 m thick (average 127.54 m) at depths between 490.5 and 1285.3 m.

Locally faulted stratiform salt deposits in south-western Poland (the Sieroszowice-Bytom-Odrzański area) may also be potentially important (**Figure 16.37**). Four rock-salt units (up to 295 m thick) occur at depths of 470 to 1510 m and contain more than 51 billion tons of rock-salt (Przeniosło, 2005). Among the many salt domes and diapirs that have not been exploited (**Figure 16.37**), only seven structures have storage potential: Rogóźno, Damasławek, Lubień, Łanięta, Goleniów, Izbica Kujawska and Dębina (Czapowski, 2006a; Czapowski et al., 2006). The most prospective are the large Rogóźno and Damasławek structures (Figure 3.42c), where the top of the salt bodies are at shallow depths (325-427 m and 446-539 m respectively (**Table 16.21**). The diapirs at Lubień and Łanięta also have favourable parameters. The two larger structures at Goleniów and Izbica Kujawska (**Table 16.21**), and the small Dębina diapir, have not been investigated sufficiently. In the Mogilno diapir, gas is stored in eight salt caverns (**Figure 16.37**) about 250 m in height and with a total volume of 416 bcm. A further 12 caverns are planned with volumes of up to 1.15 bcm. Small volumes of oil and gasoline are stored within the old caverns of the Góra diapir (**Figure 16.37**). The total volume of gas pumped into aquifers of the Polish UGS facilities described above was estimated to be 5 to 12 bcm. Salt domes that are also being considered for UGS occur in the Rogóźno, Damasławek, Lubień and Łanięta diapirs (**Figures 16.37** and **Table 16.21**).

Table 16.20 Characteristics of selected aquifers for UGS in Poland (after Reinisch, 2000). See Figure 16.35 for locations of aquifers.

Aquifer	Aquifer depth (m)	Type and age of aquifer rocks	Area (km^2)	Porosity (%)/ permeability (mD)	Hydrostatic pressure (mPa)	Volume of gas storage (bcm)
Chabowo	670-800	Sandstones – Early Jurassic (Liassic) & Early Cretaceous (Albian)	25	18-30/10-1330	6.5-7	0.5-1.5
Bielsk	1100-1200	Sandstones – Early Cretaceous (Albian + Barrenian)	9	18-19	11-12	1-2.5
Bodzanów	1050-1150	Sandstones – Early Cretaceous (Albian + Barremian)	20	15-28	10-11.5	1-2.5
Drobin	1050-1150	Sandstones – Early Cretaceous (Albian + Barremian)	10	16-20	10-11.5	1-2.5
Kałuszyn	740-800	Sandstones – Early Cretaceous	10	18-20	7.4-8	0.5-1.5
Gostynin	800-900	Sandstones – Early Cretaceous (Albian)	15	19-22	8.9-9	0.5-1.5
Tuszyn	735-858	Sandstones – Early Cretaceous (Albian)	30	11-30/10-9848	7.5-8.5	0.5-1.5

Table 16.21 Characteristics of selected Permian salt diapirs from the Polish Lowlands adapted or planned for hydrocarbons storages (salt caverns) (after Ślizowski et al., 1996, 2004; Przeniosło, 2005; Czapowski, 2006b). See Figure 16.37 for locations.

Salt diapir	Diapir size/area (km/km^2)	Salt mirror depth, min-max (m)	Top depth/thickness of caprock, min-max (m)	Salt resources (bln t)
Goleniów	4.5 × 2/9	888.0	702.2/186.8	-
Damasławek	3.5 × 5.5/16.5[1]	446-538.8	184-1050/2.5-294.1	17.69[2]
Mogilno (gas caverns)	5.8 × 1.5/8.7	220-260	84-100/160-170	5.56[2]
Góra (solution mine, oil & gas caverns)	1.2 x 1.1/1.32	103-143	19-69/several tens	1.9[2]
Izbica Kujawska	2 × 4/8[1]	224.5-556.5	143-412/27.7-207.2	1.5[1]
Lubień	2 × 2.5/3.7[1]	303-441.6	151.5-358/81.5-169	4.07[2]
Łanięta	3.3 × 3.7/9.5[1]	235.4-282.5	90-308.6/29.6-241.4	2.13[2]
Rogóźno	4.0 × 6.7/21[1]	325-427	54.5-328.8/12.8-286.3	8.61[2]
Dębina	0.6 × 0.8/0.5[1]	169.3-215	47.3-121/94-122	0.5[1]

1 Data after Ślizowski et al., 1996, 2004.

2 Resources (after Przeniosło, 2005).

Regulations and licensing

Licences for UGS storage are granted to any investor after acceptance by the Ministry of Economy. The licenses govern factors such as geological, technical and economic aspects, investment schedule and financial guarantees. The associated geological activity is regulated by the Geological and Mining Law.