Geothermal energy

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ABSTRACT

In the Netherlands, the use of the shallow subsurface (generally down to 500 m depth) for extraction and storage of heat is well established. The use of hot ground water for balneological purposes is modest; two thermal baths use water from Eocene sands at depths between 600 and 750 m, while two others exploit water from Carboniferous limestones at 400 m depth, and from Permian sediments at 900 m depth, respectively. Groundwater at greater depths is a potential source of energy. Based on subsurface temperature data, several evaluation projects were carried out in the 1980s, ultimately resulting in a number of inventory and feasibility studies. As yet, however, these studies did not lead to the actual exploitation of geothermal energy. Aquifers that are of potential interest for heating purposes occur at depths of less than 100 m to more than 3000 m in Permian, Lower Triassic and Lower Cretaceous sandstones and in two Tertiary sand units. In total, ca. 90×10^{18} J (equivalent to 2400×10^9 m^3 natural gas) of heat in place (HIP) may be present in these deep reservoirs. The fraction of this energy that may eventually be produced successfully, however, depends strongly on location-specific reservoir properties.

Keywords: Netherlands, heat in place, aquifers, geothermal gradient

Introduction

The earliest known records of subsurface temperatures in the Netherlands were obtained from a borehole, drilled in 1872 to a depth of 365 m in the city of Utrecht in the centre of the country (Harting, 1879; Visser, 1978). Between 1910 and 1960, temperatures were measured in various coal-exploration wells in the east and south of the country. Temperature data are also available from oil and gas exploration and production wells in the Netherlands onshore and offshore areas. These data show that subsurface temperatures are related to the lithology of the sediments; for instance, the geothermal gradients in the Upper Carboniferous strata tend to be high, over 4 and up to 5.2 and even 5.6°C per 100 m, due to the low thermal conductivity of coal; in contrast, the high conductivities of rock salt and anhydrite cause low gradients of 2.5°C/100 m (Visser & Heederik, 1987).

Van Dalfsen (1981) published country-wide temperature maps for 10 depth levels, from 25 m to 250 m. These maps resulted from accurate measurements of equilibrium temperatures in small-diameter groundwater piezometers. The maps show that natural groundwater flow is effective in perturbing a subsurface temperature field due to pure heat conduction. Additional temperature data allowed an update of the shallow subsurface temperature field (Van Dalfsen, 1982).

Prins (1980) published the first deep-subsurface temperature map of the Netherlands, based on oil and gas exploration data. Updates, based on larger data sets, were prepared by Ramaekers (1991) and Rijkers & Van Doorn (1997), and include maps of various depth levels. Van Balen et al. (2002) presented deep subsurface temperatures in the Roer Valley Graben and Peel Block area, concluding that, contrary to the results of previous mapping, the Roer Valley Graben is probably not a relatively cold area in the Netherlands. The temperature distribution shown in Figure 1 indicates average geothermal gradients of ca. 3 to 4°C/100 m down to 2000 m depth. The average surface temperature is ca. 10°C (Van Dalfsen, 1981).

In the Netherlands, geothermal-energy exploitation from groundwater can be regarded as a potential source of energy. The rise of oil prices in 1973 boosted the interest in this kind of non-conventional energy, resulting in a government-established 'Discussion Group Geothermal Energy' (Visser & Heederik, 1987). This group formulated various evaluation projects, ultimately resulting in a number of inventory and feasibility studies in the 1980s which did not, however, lead to the actual exploitation of geothermal energy. Studies dealing with the temperature distribution, reservoir characterization and required reservoir properties in the shallow subsurface were performed by Groundwater Survey TNO (e.g. Csonka, 1968; Van Dalfsen, 1982; Dufour, 1984). Geological inventory studies for geothermal-energy purposes were carried out by the Geological Survey (RGD, 1982, 1983, 1984, 1985). The geothermal test well Asten-2, drilled in 1987 in the province of Noord-Brabant, was not successful (Visser & Heederik, 1987; Heederik & Huurdeman, 1988). The targeted Tertiary aquifers, the Houthem (1630–1670 m below mean sea level) and Dongen (1500–1550 m) formations, Voort Member (1050–1250 m) and Breda Formation (850–950 m) showed poor reservoir development; the Vessem Member of the Oligocene Rupel Formation at 1490–1510 m below the surface (elevation ca. 25 m above mean sea level) yielded water with a temperature of 54°C, which was considered too low for the heating of greenhouses in the area.

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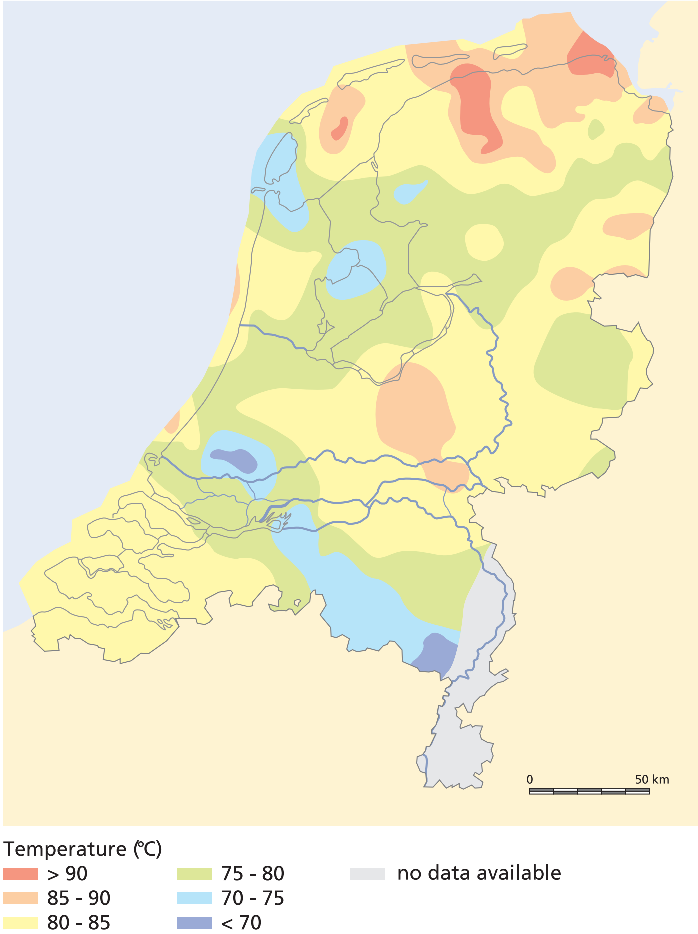

Fig. 1. Temperatures at 2000 m depth below the surface, obtained from measurements in boreholes (NITG, 2004). In the 'no data' area in Limburg, only one well (Nederweert-1) reached a depth of 2000 m.

In the past few years, the potential of geothermal energy as a sustainable energy source received renewed interest, partly as a consequence of the 1997 Kyoto protocol which aims at achieving a worldwide reduction in CO_2 emissions. Moreover, recent oil-price increases have boosted the interest in geothermal energy for application in both district heating and greenhouses.

Geothermal-energy production

From a geological point of view, geothermal energy projects require formation water that is of sufficiently high temperature and a reservoir rock that allows the production of sufficiently large volumes of water. The temperatures required depend on the kind of application. They are, for example somewhat lower for greenhouses than for district-heating systems which generally have an inlet temperature of 70°C. In the Netherlands, water temperatures of 70°C or higher are found in aquifers deeper than 2000 m and temperatures around 45°C in aquifers at depths of 1000 to 1200 m. Figure 1 shows the temperature distribution at 2000 m depth.

The transmissivity, i.e. the product of thickness and permeability of the aquifer, should be sufficient to permit a production of several thousands of cubic metres per day. It is the main risk factor and often the reason that potential aquifers and locations turn out to be unsuitable. In practice, only thick or very permeable aquifers are prospective.

Both in the storage of energy (heat and also cold) at shallow depth and the extraction of heat from greater depth, open or closed systems can be employed (Table 1). The water used in an open system circulates from time to time freely through the aquifer. The liquid used to transport heat in a closed system on the contrary always circulates through various kinds of pipes and vessels.

Shallow applications

In the Netherlands, combined heat and cold storage is applied at many places, using groundwater in shallow aquifers (generally at less than 500 m depth) as the main carrier of the energy in a two-well system. During wintertime, heat is extracted from groundwater produced by a 'hot' well, and after heat extraction above ground, the cooled water is injected through another 'cold' well. In summertime the system is reversed and groundwater is produced from the 'cold' well, and after cold extraction, the heated groundwater is pumped back through the 'hot' well. In general the total heat and cold added to and subtracted from the aquifer are balanced on a yearly basis. The water temperature in this open circuit ranges from about 5 to 25°C. The thermal power is generally between 200 and 20 000 kW. Most applications are in offices and commercial buildings. More than 300 systems have been installed (Van Heekeren et al., 2005).

A second shallow-subsurface application is a closed system with borehole heat exchangers. In general this is used down to 150 m. A fluid is pumped down a borehole, through the heat exchanger(s), and then back to the surface via a separate tube inside the same borehole. During

Table 1. Geothermal-energy production methods.

Depth range	Open systems	Closed systems
Shallow (down to 500 m)	Heat and cold storage Heat storage	Shallow borehole heat exchangers
Deep (down to > 4000 m)	Low-enthalpy geothermal energy Hot Dry Rock	Deep borehole heat exchangers

wintertime the heat is extracted aboveground from the circulating fluid, gradually cooling the immediate surroundings of the well. In summertime the system is reversed for cooling purposes. Here too a balance between heat and cold is necessary. According to Van Heekeren et al. (2005), over 1100 of this type of systems were in operation by the end of 2004, mainly for small-scale applications such as single-family houses and small-size office or commercial buildings. In the houses, most of the systems are used only for heating purposes. In buildings, however, the systems are mainly applied for both heating and cooling, using the underground both as a heat source and a heat sink. The systems have a thermal power ranging from 50 to 100 kW.

A third shallow application is the storage of heat. Surplus heat is temporarily stored in the subsurface aquifer and is extracted at a later stage. This is realized at a few (< 10) locations only.

Deeper applications

In the applications installed in the deeper subsurface, the extraction of heat is the main purpose. They use geothermal energy in the strict sense. At the moment this kind of application is not realized in the Netherlands. However, the sharp increase in energy prices, combined with Kyoto-protocol measures, leads to an increasing interest in low-enthalpy geothermal energy, and the realization of such a geothermal project is expected within the next few years. The first exploration licence (2006) for this purpose has been granted to a greenhouse farmer in Bleiswijk (Zuid-Holland). High-enthalpy ($T > 180°C$) geothermal energy sources such as geysers and steam fields are not present in the Netherlands.

The application of deep geothermal energy for the production of heat is occasionally (Neustadt-Glewe, Germany, and Altheim, Austria) combined with the production of electricity by means of binary conversion techniques (Organic Rankine Cycles or Kalina techniques). These techniques apply (organic) fluids with low boiling temperatures to drive a turbine. Their efficiency is still relatively low, but the remaining heat is used for heating purposes. Currently the German government promotes this technique by guaranteed high prices for the electricity, boosting the interest in geothermal energy to a high level.

Deep low-enthalpy geothermal systems can be open or closed. Low-enthalpy heat extraction operates by means of a two-well system (doublet), which consists of a production well that taps the water from the aquifer and a second well through which the cooled water is re-injected into the aquifer. Operations involving such a geothermal doublet take place in France, Germany, Austria, Hungary and other European countries. In general, the aquifer has temperatures > 70°C, a relatively good permeability (> 300 mD) and a thickness of preferably > 30 m. Its depth is mostly less than 3400 m. An important, and restricting condition in these operations is the balance between heat supply and heat demand. The drilling of a doublet results in high initial investment costs, which have to be balanced by a sufficiently high demand. A doublet can have a thermal power of up to 10 MW, which is enough for the direct heating of about 4000 houses. Such an amount of power would also be sufficient for one of the larger greenhouses as used in the Netherlands today. The cost of heat transport at the surface calls for a short distance between supply and demand.

A second open system is the Hot Dry Rock (HDR) concept. Several European areas with relatively high geothermal gradients have temperatures up to 200°C at depths of 4000 to 5000 m. Cold water is injected into rocks of low to zero permeability, which have been fractured ('fracked') artificially, allowing cold water to migrate from injection to production well. During its migration the water is heated by the surrounding rock, resulting in production temperatures of 180 to 200°C. The main purpose is to generate electricity by means of binary conversion techniques. At the moment, Hot Dry Rock techniques are experimentally applied in Soultz (Alsace, France). If successful, HDR will have a high potential throughout Europe. A new experimental site is in Gross Schoenebeck (eastern Germany), where a borehole is deepened to 4000 m. The target comprises the volcanics and low-permeability clastic rocks of the Lower Rotliegend. A comparable geological situation occurs locally in the eastern Netherlands as well.

A third application, currently in progress, is the extraction of heat from water in the galleries and shafts of the former coal mines in Zuid-Limburg.

Closed deep systems mainly utilize Deep Borehole Heat Exchangers (DBHE). Such an exchanger extracts heat from rock layers at depths less than 2800 m. Water circulates through a co-axial system, downwards along the borehole casing and upwards via an in-hole production tube. The generated thermal power is about 300 to 500 kW. Operators of this kind of system try to maintain an optimum balance between the production of heat and the influx of heat. Such systems are active in a few places in Germany and Switzerland, where they are used for heating purposes. Here too the distance between the location of the exchanger and the place of heat demand is critical as a large transport distance is costly. The Deep Borehole Heat Exchangers currently in operation are all situated in areas with a normal (30°C/km) geothermal gradient.

Aquifers

Aquifers of sufficient thickness and sufficiently high permeability and temperature, suitable for the extraction of geothermal energy, occur mainly in Noord- and Zuid-Holland, Noord-Brabant, and in the northern and eastern

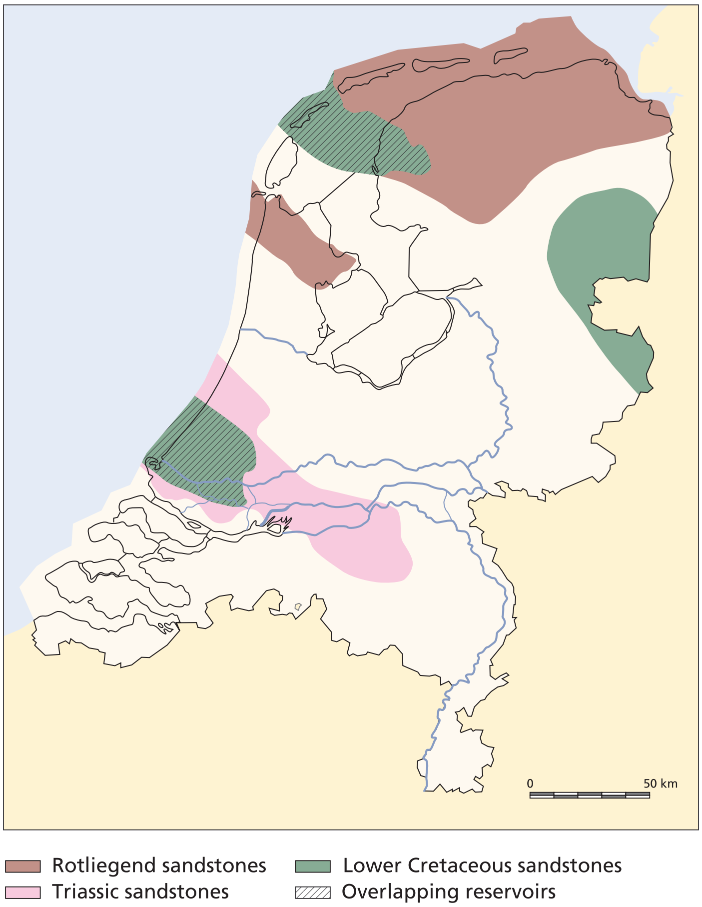

Fig. 2. Distribution of deeper aquifers which are potentially most suitable (T > 60°C and sufficient transmissivity) for the extraction of geothermal energy (cf. Table 2). Localized potential occurrences are not indicated. Neither are Tertiary aquifers which are present under much of the Netherlands (after NITG, 2004).

parts of the Netherlands (Fig. 2). In stratigraphic order, these aquifers are present in:

- Permian, Rotliegend sandstones of the Slochteren Formation in northern Noord-Holland and in Friesland, Drenthe and Groningen;
- Lower Triassic sandstones of the Main Buntsandstein Subgroup in Zuid-Holland and Noord-Brabant, locally also in the eastern Netherlands and Zuid-Limburg;
- Lower Cretaceous sandstones in Zuid-Holland, Friesland and the eastern Netherlands;
- Tertiary sands (Brussels Sand Member and Breda Formation): present at shallow depths under large parts of the country.

The reservoir parameters are listed in Table 2.

Water from the Eocene Brussels Sand Member is locally used for balneological purposes. In 'Aqua Plaza', Ameland island, the sand occurs at 750 m depth and has a temperature of 37°C. In 'Fontana', Nieuweschans (eastern Groningen), its depth is 633 m and its temperature 28°C. The mineral-rich water exploited at 'Thermae 2000' in Valkenburg (Zuid-Limburg) is derived from limestone of the Dinantian Zeeland Formation at approximately 400 m depth; its temperature is 24.5°C (Krings & Langguth, 1987). At Arcen (northern Limburg), mineral-rich water of 42°C is obtained from Permian sediments at 892 m depth. Geothermal energy from aquifers in Pleistocene sands at about 50 m depth is currently applied on a rather modest scale, notably in glasshouse horticulture in Zuid-Holland (Van de Braak et al., 2001).

Potential

The potential for deep geothermal energy in the Netherlands has recently been calculated according to the method proposed by Haenel & Staroste (1988), which determines the 'Heat In Place' (HIP) of the aquifers of interest. Separate calculations were made for the three main intervals, i.e. the Permian Rotliegend, the Lower Triassic and the Lower Cretaceous sandstones. A HIP calculation takes into account the average thickness of a sandstone layer, the average difference between aquifer temperature and surface temperature, and the lateral extent of the reservoir. Moreover, it also involves the heat capacities of the rock matrix and the pore water, which are calculated separately on the basis of the average reservoir porosity.

The results of the calculations, as reported by Lokhorst & Van Montfrans (1988) and Van Doorn & Rijkers (2002), are shown in Table 2. These results carry a considerable degree of uncertainty, in the order of 50 to 80%. They should not, therefore, be used to assess the local potential for geothermal energy; they only indicate an overall figure for the entire aquifer. In total, ca. 90×10^{18} J (equivalent to 2400×10^{9} m^{3} natural gas) of HIP may be present, i.e. the heat, relative to the average 10°C temperature of the land surface, occurring in the three deeper sand-rich stratigraphic intervals which might be suitable for the extraction of geothermal energy. The amount of this energy that may eventually be produced successfully, however, depends strongly on location-specific reservoir properties.

Finally, it should be noted that the efficiency of transporting heat to users at the surface is limited by the costs of transporting hot water over long distances. The matching of the subsurface-related heat supply and the surface-related heat demand is of utmost importance. The availability of a pipeline infrastructure to transport heat is a major factor in assessing the economic potential of a geothermal energy project.

Benefits and risks

The application of geothermal energy has several benefits, of which the most important are:

- it can contribute significantly towards the reduction of greenhouse gases, because the emission of CO_2 (mainly generated by the necessary pumping) is very low; the emission of other greenhouse gases is negligible;

Table 2. Reservoir parameters and Heat In Place (HIP) for aquifers in sandstone and sand in the onshore Netherlands (sources: Lokhorst & Van Montfrans, 1988; Van Doorn & Rijkers, 2002; NITG, 2004).

Aquifer	Depth (m)	Gross sand thickness (m)	Porosity (%)	Perm. (mD)	Temp. (°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	Max. 3000	Max. 90	3
Lower Saxony Basin (especially SE Drenthe)	800–1800	3–65	15–20	220–500	40–80	0.4
NW Friesland	1800–2100	10–200	15–22	1–30	70–80	
Tertiary sands						
Brussels Sand Mbr	100–1150	0–135		Max. 600	15–45	
Breda Fm	< 835	Variable	30–35	50– > 200		
Total HIP						> 90.4

- it does not entail visual or noise nuisance;
- the security of supply is high; in principle, a geothermal plant can operate all year long and its capacity is independent of seasonal fluctuations and weather conditions;
- the technology is safe and proven, mainly based on extensive experience in oil and gas production.

A few drawbacks can be foreseen in the Dutch situation. The aquifers, suitable for geothermal exploitation are the same as the oil and gas-bearing reservoirs, implying considerable overlap (Fig. 2). A deep-seated geothermal project positioned close to a producing oil or gas field or a gas or CO_2 storage facility, therefore may cause subsurface interference. The extraction of geothermal energy may affect the pressure distribution in or around the oil or gas field or the storage facility. A recent simulation study (Brouwer et al., 2005) concerning the effects of overpressure and temperature changes in the Lower Cretaceous IJsselmonde Sandstone Member, however, shows that, if re-injection of water takes place under overpressure conditions, the pressure changes in the direct vicinity of the wells due to the extraction of geothermal energy are limited, i.e. no more than 1 bar at a distance of 1 km. The simulation also shows that thermo-elastic effects may occur as well, depending on the temperature of the injected water. These may amount to 50 bar if the formation is cooled by more than 50°C, which would locally cause a compaction of 2 to 3 cm at reservoir level (ca. 1100 m); the effects at surface would be negligible. Such investigations are important in the Netherlands, where public concern about soil subsidence and seismicity due to gas production plays an important role in discussions on the use of the underground.

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