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GEOTHERMAL REINJECTION IN SEDIMENTARY BASINS

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ABSTRACT

Low-temperature sedimentary geothermal systems belong to one of the main types of geothermal resources worldwide. Experience from reinjection practices is important to understand the main characteristic parameters of a geothermal system, in order to avoid a failure of its utilization, e.g. through overexploitation. This report presents examples of good reinjection practices in sedimentary systems in different European countries, where reinjection is a part of the sustainable management of geothermal resources. Besides this, the report presents information on the geothermal potential in Romania, with main emphasis on reservoirs and geothermal specifics in the Balotesti area, north of the capital of Bucharest. The experience of countries such as France and Germany has shown that reinjection should be planned simultaneously with production for geothermal district heating systems. The lessons learned in these countries should be the basis of developing geothermal reinjection in countries with limited experience of reinjection, such as in Romania. The reinjection design should focus on maintaining the reservoir pressure, but it is also important to predict the long-term thermal breakthrough time for the production wells used. The report also presents recommendations aimed at supporting a considerable increase in the utilization of geothermal resources in Romania as well as their sustainable management.

1. INTRODUCTION

Geothermal energy refers to the thermal energy that is flowing and contained within the Earth. It is a renewable energy source, available worldwide. Exploitable geothermal resources can be found especially in regions where the geothermal gradient is normal or high. Volcanic regions have the highest geothermal potential, but geothermal energy may also be found in sedimentary regions as warm ground water, often sufficiently warm to be used for heating. Shallow thermal energy can be utilized through shallow boreholes and ground source heat pumps.

Geothermal systems can be classified based on the geological settings as (Saemundsson et al., 2011):

1. Volcanic geothermal systems associated in general with volcanic activity where the heat source is hot intrusions or magma. The reservoir temperature in those systems at 1 km depth is above 200°C.

2. Convective fracture systems located in tectonically active areas with above average geothermal gradient. The heat source is the hot crust where water has circulated down to at least 1000 m depth through fractures. In general, these are intermediate- or low-temperature systems with reservoir temperature below 150°C at 1000 m depth
3. Sedimentary geothermal systems are the most common geothermal systems, which can be found worldwide. In general, these are low-temperature systems.
4. Geo-pressured systems are fairly deep and are located where there is an impermeable layer of sedimentary cap rock that traps the geothermal reservoir. The temperatures in these systems range from 90 to 200°C at 1000 m.
5. Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS) consist of volumes of rocks heated by volcanism or other high heat sources. This kind of geothermal resource often has low permeability or is virtually impermeable, hence it cannot be used in a conventional way. EGS systems usually have production-reinjection doublets.
6. Shallow geothermal is related to the normal heat flux near the surface or energy stored in the groundwater systems. Shallow geothermal is exploited using ground source heat pumps.

The proper and sustainable exploitation of geothermal resources involves production and reinjection of geothermal fluids. Geothermal reinjection involves injecting energy-depleted fluid back into the geothermal reservoir system. The quantity of geothermal water injected into a geothermal reservoir is not equal to the amount of produced water in most cases, and often just some portion is returned into the reservoir. Reinjection started out as solution for wastewater disposal and but in recent years it has become a necessary part of sustainable and environmentally friendly utilization of geothermal resources.

In most cases reinjection is considered a part of comprehensive geothermal resource management as well as sustainable utilization of geothermal resources. Reinjection provides an additional recharge to the geothermal systems and reservoir pressure support. In this way, more thermal energy can be extracted from geothermal systems. Reinjection will increase production capacity of geothermal reservoirs, which counteracts the costs for reinjection and exploitation projects. In enhanced geothermal systems (EGS) reinjection is a crucial part.

Some operational problems can appear in projects which involve reinjection, such as cooling of production wells and scaling in reinjection equipment and injection wells, because of the precipitation of chemicals in the water. Before starting a reinjection project some extensive studies and research regarding successful reinject operation need to be performed.

The status of reinjection at the end of last century was described by Stefansson (1997). Axelsson (2008 and 2012) and Rivera-Diaz et al. (2016) provide more recent reviews, including information on associated technology, research and reinjection testing. This paper reviews the key role of geothermal reinjection into the reservoir, geothermal resource management and management of long-term reinjection. The most important tool available for studying the relation between production and reinjection is tracer testing, discussed also in the paper mentioned above (Axelsson, 2012).

This report reviews some projects from sedimentary geothermal systems in different European countries, where geothermal reinjection is used in the projects. The purpose of this report seeks to exemplify these projects as good practice of geothermal reinjection in sedimentary basins in order to develop geothermal district heating systems. For this project twenty European countries were analysed: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Ireland, Macedonia, Netherlands, Norway, Poland, Serbia, Slovakia, Slovenia, Sweden, Switzerland and Romania. Some of these countries perform geothermal reinjection on a small scale and in these cases the geothermal water is used mainly for recreational and health purposes. For the countries which perform geothermal reinjection the main geothermal reservoirs are presented, including successful projects which started in last decades in order to ensure the heat supply for municipalities. In this paper projects from ten European countries are reviewed: Austria, Croatia, Czech Republic, Denmark, France, Germany, Hungary, Poland, Slovenia and Hungary. The report also shows the Romanian geothermal potential with main reservoirs and geothermal specific to the Balotesti area of Ilfov County. The main purpose of this paper is to show the importance of reinjection when utilizing geothermal resources for district heating system.

2. EVOLUTION OF REINJECTION

Sedimentary basins are, as mentioned above, the most common geothermal systems found in the world. Sedimentary basins are layered sequences of alternate permeable (limestone, sandstone) and impermeable strata (shale or mudstone). Geothermal water found in sedimentary rocks is commonly brine with variable temperatures. The temperatures depend on the depth of the permeable rocks in the geothermal system. Existence of these permeable sedimentary layers at depth of >1 km combined with average geothermal gradients (>30°C/km), or above that, explains the existence of sedimentary geothermal resources. The systems are more conductive in nature than convective.

Several sedimentary basins exist in Europe, for example the Aquitaine basin, Molasse basin, Paris basin, Vienna basin, Pannonian basin and N-German basin, which are used for geothermal utilisation. The depth of geothermal systems may vary from 1 up to 5 km, the heat flow differs widely and the level of fluid salinity varies from relatively fresh ground water to high salinity brine (250,000 ppm).

Natural recharge of geothermal fluid in sedimentary system is not the same as for volcanic or convective systems, which leads to minimal recharge and therefore reinjection is needed in order to maintain the reservoir pressure level. Geothermal waste water disposal is often mandatory after using it for the main purpose of harnessing geothermal energy (heating, producing electricity, greenhouses etc.). For sedimentary geothermal systems, reinjection doublets are commonly used (production-injection well doublet). In this way the utilization of a geothermal system is ensured as sustainable during long-term operation and also environmentally friendly.

Figure 1 presents a schematic sketch of a sedimentary basin with a geothermal reservoir located at 2-4 km depth, including faults and fractures, which can play a role in the recharge of the geothermal basin reservoir. The figure also shows how the geothermal temperature profile in sedimentary basins is usually related to depth.

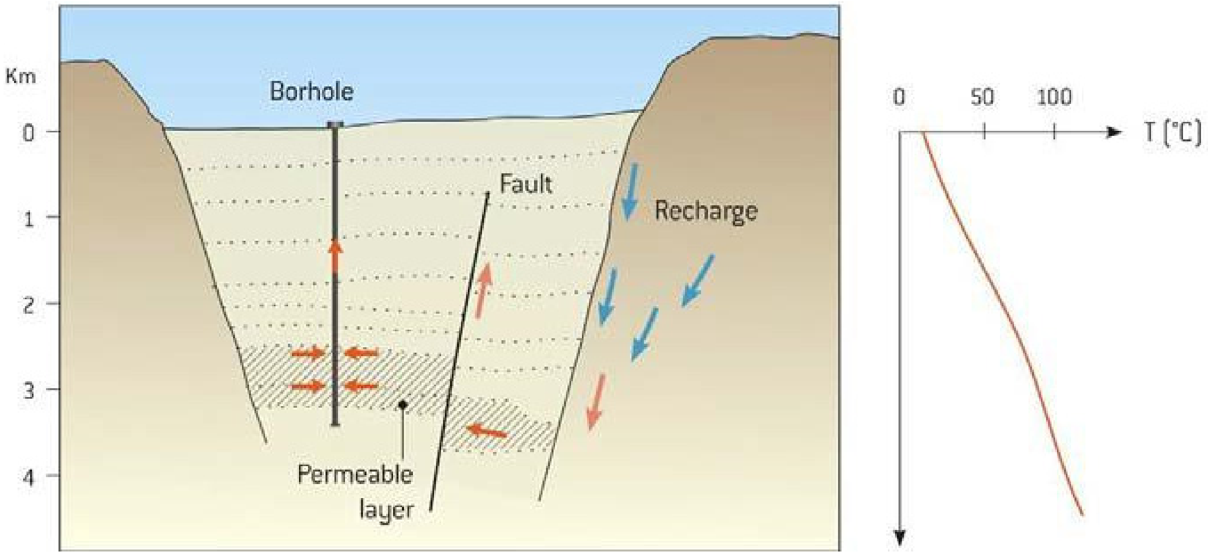

FIGURE 1: Sedimentary basin geothermal reservoir with recharge and geothermal gradient profile in the basin (Saemundsson et al., 2011)

Sedimentary rocks with pore pressure exceeding the normal hydrostatic pressure gradient contained in geothermal sedimentary basins are classified as geo-pressured geothermal systems. In such sedimentary reservoirs fluid is caught in stratigraphic traps similar to geo-pressured oil and gas reservoirs and the fluid pressure may be close to lithostatic values. Geo-pressured geothermal sedimentary systems are e.g. known in Hungary and the northern part of the Gulf of Mexico basin, but these fields are not exploited at the moment (Saemundsson et al., 2011).

Even if geothermal reinjection has focused on high-temperature geothermal fields, reinjection in low-temperature fields, especially in sedimentary basins, has become the norm in many countries, because of sustainability. Reinjection in geothermal sedimentary systems started in 1969, first in the Paris Basin in France, which includes a large geothermal resource associated with the Dogger limestone formation covering a surface greater than 15,000 km^2. Geothermal water is mainly used for district heating in the Dogger reservoir and the production is based on using production-injection doublets. The utilisation started as a result of the first oil crisis. The Paris doublets are separated by a distance of close to 1 km. This distance is maintained to prevent or minimise the cooling of the reservoir due to the reinjection and has so far caused no cooling in the production wells (Ungemach et al., 2005). Another example where reinjection has become an important part of harnessing geothermal fields is in Tianjin in China (Axelsson, 2008; Wang and Lin, 2010).

Reinjection provides supplemental recharge to the geothermal field and is used to counteract draw-down due to production. Pressure response of a geothermal system controls its production capacity, with reinjection being able to increase the production capacity of a geothermal reservoir. Most of the thermal energy of a geothermal system is stored in the reservoir rocks, while only a small percent (10-20%) is stored in the reservoir fluid (Axelsson, 2012). Injection wells or injection zones are located in different locations depending on their intended purpose. They are designed and drilled to intersect feed zones or aquifers. The main problems which may occur during reinjection are:

1. Cooling of production wells;
2. Silica scaling in surface pipelines and injection wells, especially in high-temperature systems;
3. Corrosion and types of scaling in both, low- and high-temperature geothermal fields;
4. Clogging of aquifers next to the reinjection wells in sandstone reservoirs.

In geothermal studies, research, development and resource management regarding reinjection and tracer testing is an important tool because it provides information on the connections between the production and reinjection wells and on the possible rate of cooling of the production wells during long-term reinjection of cold fluid back into reservoir. Reinjection is a part of modern geothermal system management for geothermal energy production, which can improve the efficiency and increase the long-term utilisation of the geothermal resources.

3. STATUS OF GEOTHERMAL REINJECTION IN DIFFERENT EUROPEAN COUNTRIES

Injection has been a part of many geothermal projects in Europe in geothermal fields of both volcanic and sedimentary type. Optimal development and management of geothermal resources led to development of the projects, which have harnessed geothermal water for district heating in some countries for more than 30 years. It is important to evaluate the past experience of reinjection practices, understanding the characteristic parameters of the reinjection systems for sustainable development. This applies especially in countries were large-scale reinjection hasn't started yet, such as Romania. The geothermal doublet system is the system commonly used for reinjection in sedimentary system in European countries. Here, it can be mentioned that reinjection is not compulsory in some countries but has become the key of long-term running of district heating systems in others. Certainly, there are some risks involved with reinjection practices but these can be mitigated by forerunner studies.

3.1 Austria

Austria (area 83,871 km², 8.5 million inhabitants in 2014) is subdivided into different geological units with different conditions for hydrogeological and geothermal water. In Austria utilisation of deep geothermal water is mainly from the Molasse basin of Upper Austria and to a minor extent in the Styrian basin. In 2014, Austria has drilled 75 geothermal wells, as summarised in Figure 2 and Table 1, with a total length of 129 km (Goldbrunner, 2015).

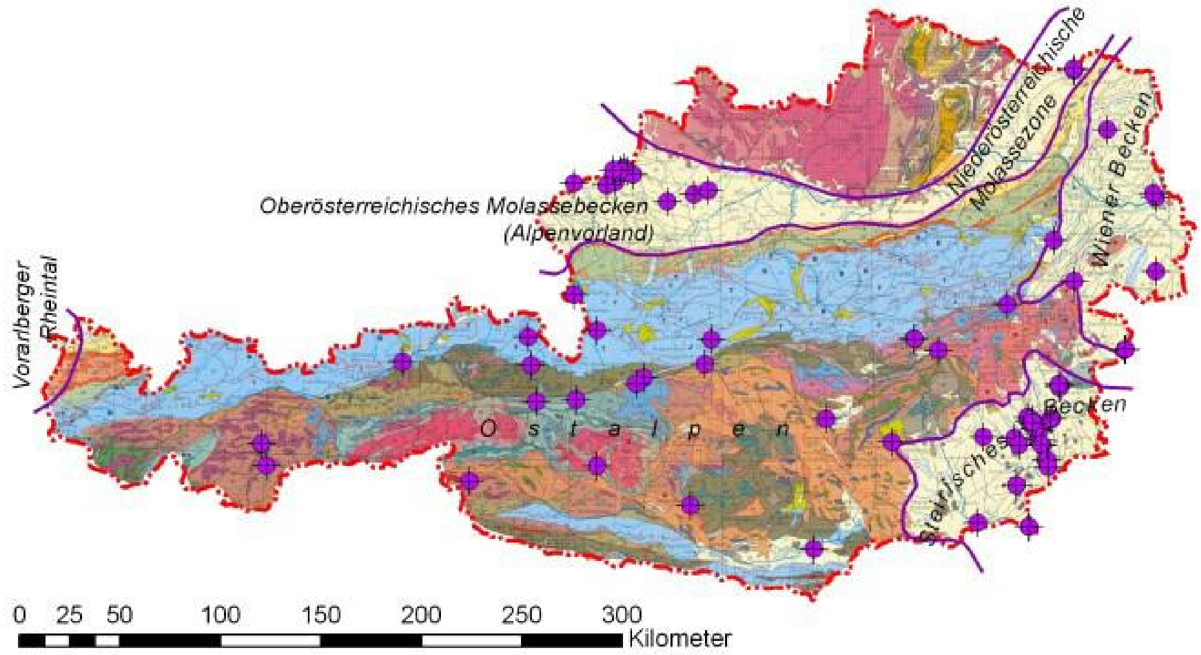

FIGURE 2: Location of the geothermal wells in Austria (Goldbrunner, 2015)

TABLE 1: Number and total length of geothermal wells in Austria (Goldbrunner, 2015)

Geological unit	Total wells drilled	New wells drilled 2010-2014	Total length of new wells [m]	Total length of all wells [m]
Styrian basin	28	2	6,578	48,100
Upper Austrian Molasse basin	3	2	4,810	28,236
Vienna basin and lower Austrian Molasse basin	8	1	4,223	12,605
N-Calcareous Alps and upper Austroalpine units (mainly carbonate rocks)	7			14,802
Lower, middle and upper Austroalpine units (mainly crystalline rocks)	18			24,618
Pannonian basin	1			860
Total:	**75**	**5**	**15,611**	**129,221**

The Geinberg project started in 1980 and is located in the upper Austrian Molasse basin. The first well in this project was drilled as a hydrocarbon exploration well into the Malm aquifer. Hot water discovered in this well, has been used for geothermal direct use. Decrease of pressure in the reservoir together with the growing demand for geothermal utilisation led to the drilling of a second well in the area, completing a doublet (production-reinjection). The new well "Geinberg Thermal 2" was planned as a deviated reinjection well located in the vicinity of the existing well, "Geinberg 1". The reinjection well was drilled at a distance of 1600 m from the production well, into a deep-groundwater carbonate aquifer to a total depth of 3155 m. The wellhead temperature is around 100°C.

The utilization in Geinberg is cascaded, including industrial processes in the dairy industry, district heating in the village of Geinberg and the thermal resort and spa of Geinberg. The use of water in the spa and greenhouse heating require a maximum temperature of 70°C. In this case, reinjection of geothermal water reaches a temperature of minimum 30°C, thus allowing the reinjection to be done without pumping, only by gravity (Goldbrunner et al., 1999).

In the Upper Austria project in Altheim a decision to drill a well for geothermal production was taken in 1989. The production well was drilled to a depth of 2300 m and the temperature obtained was 106°C. In 1994 it was decided to drill a reinjection well in order to maintain the water level in the Malm reservoir. The project for the reinjection well was financed by the European Commission (35%), the local government of Upper Austria and the federal government of Austria. In 1998 one more well was drilled, 40 m from the first one and after 8 months of drilling the final depth of 3100 m was reached. The tests performed after drilling revealed that the well could produce hot water with a flow of 100 L/s at 93°C.

The Altheim project was the first geothermal power plant in Europe which harnesses low-enthalpy geothermal water for producing electricity with a Rankine turbogenerator. Information about the ORC turbogenerator used in the Altheim project is presented in Table 2. After using the geothermal water for producing electricity the waste water is reinjected into the Malm reservoir at 70°C (Pernecker and Uhlig, 2002).

TABLE 2: The Altheim ORC turbogenerator performance data sheet (Pernecker and Uhlig, 2002)

Geothermal water inlet temperature	106°C
Geothermal water outlet temperature	70°C
Geothermal water flow rate	81.7 kg/s
Cooling water flow rate (about)	340 kg/s
Cooling water inlet temperature	10°C
Cooling water outlet temperature	18°C
Electric generator	Synchronous, low voltage
Net electric power output	1000 kW

Another geothermal district heating project is found in the district town Ried im Innkreis (11,400 inhabitants in 2013). The first well (Mehrnbach Th 1) of the geothermal doublet was intended to reach the Malm aquifer at 2,500 m. After encountering Malmian limestones at a depth of only 1,765 m it had to be recognized that the bore had landed on the up-thrown block of the Ried fault. Mehrnbach 1a cut across some 600 m of upper Cretaceous mainly sedimentary rocks and tapped the Malm aquifer at 2,354 m and penetrated the whole thickness (245 m) of Malm carbonate rocks (limestones and dolomites) and some 20 m of Basal sandstone and finally tapped the top of the crystalline basement at 2,598 m. The horizontal displacement at end depth was some 300 m. The second well (Mehrnbach Th 2) was located at the up-thrown block of the Ried fault some 1,300 m apart from well Mehrnbach Th1/1a.

From October to December 2012 a combined pumping and reinjection test was performed using Mehrnbach 1/1a as a production well and Mehrnbach 2 for injection. The production temperature was 105°C at a flow rate of 64 L/s. Upon detection of pressure reductions in Bavarian balneological wells some 16 km from Mehrnbach the function of the boreholes was reversed now using Mehrnbach Th 2 as production well and Mehrnbach Th 1/1a for reinjection. The trial operation of the geothermal doublet started in February 2014 (Goldbrunner, 2015).

3.2 Croatia

Croatia has both intermediate- and low-temperature geothermal fields, as shown in Figure 3. They are located in the north-eastern part of the Pannonian basin and in the south-western Dinaric Alps

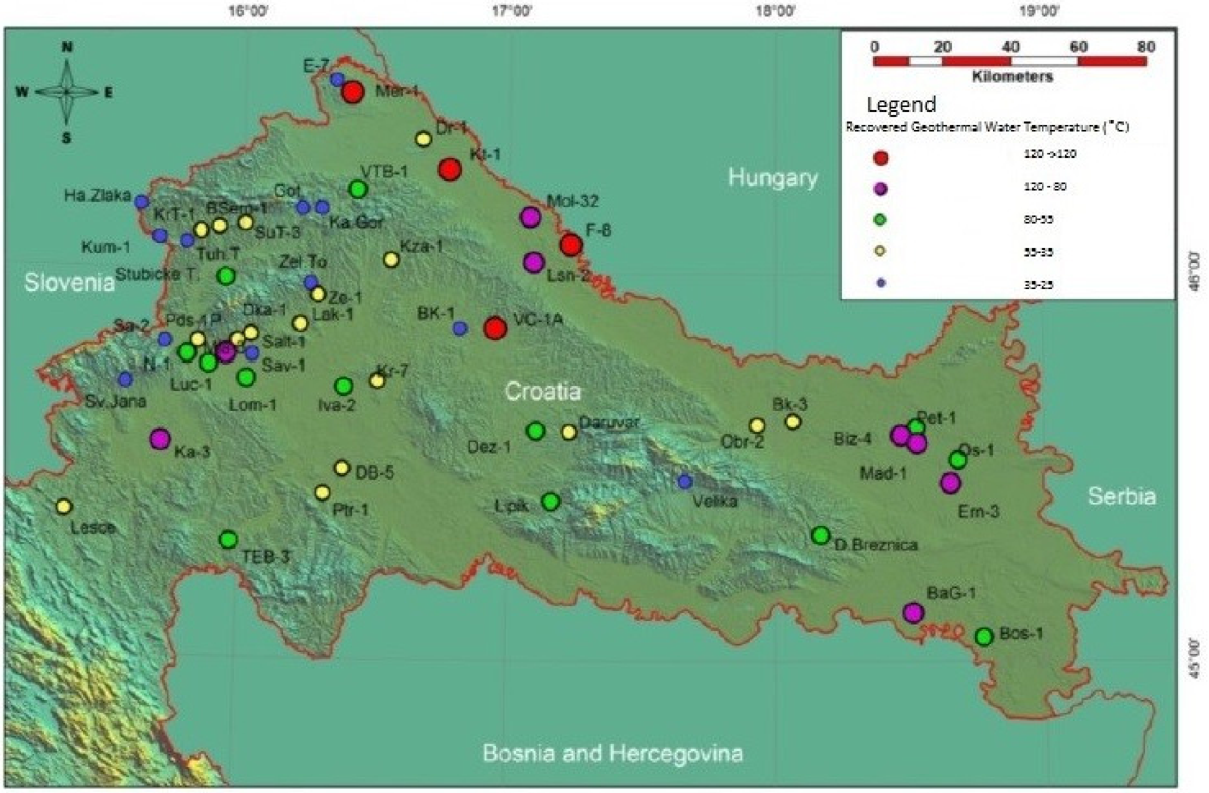

FIGURE 3: Geothermal water resources in the Republic of Croatia (Kolbah et al., 2015)

(Dinarides). In the Dinaric part (low-temperature fields) an ongoing collision of the Adriatic carbonate platform with the Eurasian plate accounts for crustal thickening. In the carbonate rocks encountered in the Dinaric part, fracture porosity caused by tectonic events has been enhanced by carbonate dissolution and this kind of fracturing increases rainwater infiltration into the ground causing reservoir cooling. Because of this, geothermal projects are mainly in the northeastern part of the country. The most common geothermal utilisation in Croatia is recreation and balneotherapy (Serpen and Aksoy, 2016).

Even though the geothermal potential to produce electricity is relatively high (Lunjkovec – Kutnjak and Velika Ciglena), Croatia has not built an electric power plant, until the first geothermal plant was planned in the Velika Ciglena geothermal field after 2015. Croatia has 27 locations with developed geothermal direct use and the development is growing through new exploration licenses: Bošnjaci Sjever (Bos-1) and Sveta Nedelja (N-1) (Kolbah et al., 2015).

In the last 80 years more than 3500 wells have been drilled for oil and gas in Croatia and in the Velika Ciglena geothermal field four oil wells were drilled in the 1990s, now abandoned. The first exploration well, VC-1, was drilled to a depth of 4790 m with a temperature of 170°C. The second well, VC-1A, was drilled at the same location. Analysis of geophysical logs indicated a porosity of 30% in the upper zones, with temperature and well logging indicating five permeable zones in well VC-1A. Constant temperature was observed from the top of the reservoir down to 3600 m indicated that the permeable zones in both wells were connected, through the same reservoir. In 1995 it was decided to harness geothermal water for a geothermal power plant with a capacity of 4.7 MW_e using well VC-1A for production and VC-1 for reinjection. In 2013 a new project was scheduled and developed, using two other abandoned oil wells for reinjection, namely Ptk-1 and VC-2 located at a distance of 2 km from the production wells. As a result, Velica Ciglena became the first geothermal power plant project in Croatia with 16.5 MWe gross and 14 MWe net capacity, where wells drilled for oil exploration are used for producing electricity (Serpen and Aksoy, 2016).

Another example of a geothermal system which harnesses water (80°C) from a low-temperature field for heating in a sports centre including sport halls and swimming pools, is in Zagreb (locality Mladost), the Croatian capital. There, a geothermal doublet has been in operation since 1987 without problems during reinjection. Utilisation of geothermal waters and/or energy in new locations such as Terme Zagreb (using the wells located in Mladost), Draškovec (Međimurje County in the north of Croatia) and Šmithen (near Slovenian border) will use geothermal waters in cascaded systems for facility heating, hot water preparation, spa and recreation, greenhouse heating and/or fish farming.

At Harina Zlaka in NW-Croatia, near the Slovenian border (Sutla River), hot springs in Croatia which yielded 3.7 L/s of 33°C hot water dried up as a result of production from two wells drilled in 1970 in Slovenia to supply a spa, tapping the same aquifer that fed the spring. In 1997, on the Croatian side of the Sutla River, two exploration wells were drilled. These wells produced cold water and the studies conducted showed that wells located on the Slovenian side had reduced the pressure in the geothermal aquifer causing a mixing of cold and hot water. This case showed the need of a bilateral management of geothermal water between Croatia and Slovenia, such as is in place between Hungary and Slovenia, which established a bilateral Slovenian-Hungarian Water Management Commission in order to maintain water quantities, chemical composition and temperatures in transboundary geothermal aquifers (Borović and Marković, 2015).

3.3 Czech Republic

Geological structures of the Czech Republic include two different geothermal domains: the Bohemian Massif, formed by granite bedrock of the Bohemian Massif and covered by sedimentary formations, and the Moravian part of the Carpathian structure with variable thicknesses (few hundred metres to >6000 m) of sedimentary layers. The geothermal potential of the Czech Republic is variable depending on the geothermal and geological fields; highest heat flux being measured in the Bohemian Massif in the northern part of West Bohemia. Just one project, located at Litomerice, has been under development for power generation, the other geothermal resources are used for spas, wellness centres, swimming pools and heating (Jirakova et al., 2015).

The Pasohlavky geothermal area was discovered 20 years ago during mining for oil and gas. The area is located in the south-eastern part of the Czech Republic, in the Vienna Basin. Two wells, Musov-3G and Pasohlavky-2G, located at distance of 2600 m from each other, supply hot water for a spa in Pasohvlasky village. The well logs performed in well Musov-3G confirmed a heat flux of 48.4 mW/m^2 and a temperature of 49.7°C (48°C at wellhead) at a depth of 1,455 m. The outflow reached 7-17.2 L/s with a water-level draw-down of 47.8 m. Well Pasohlavky 2G was drilled for reinjection in the area and during hydrodynamic testing 40 L/s were pumped without significant draw-down in water level, with an outflow temperature of 40°C (Jirakova et al., 2015).

3.4 Denmark

Geothermal potential in Denmark is mainly related to two deep sedimentary basins, the Norwegian-Danish subsurface basin and the northern rim of the North German Basin, which constitutes the southernmost part of the country. The Norwegian-Danish basin contains formations with sandstones which can used as geothermal reservoirs. These are primarily the Lower Triassic Bunter sandstone formation, the Triassic Skagerak formation, the Upper Triassic – Lower Jurassic Gassum formation, the Middle Jurassic Haldager sand formation and the Upper Jurassic – Lower Cretaceous Frederikshavn formation (Figure 4). The Bunter Sandstone formation located in the North German Basin represents the main geothermal reservoir, while the Gassum Formation is only sporadically preserved at shallow depths (Røgen et al., 2015).

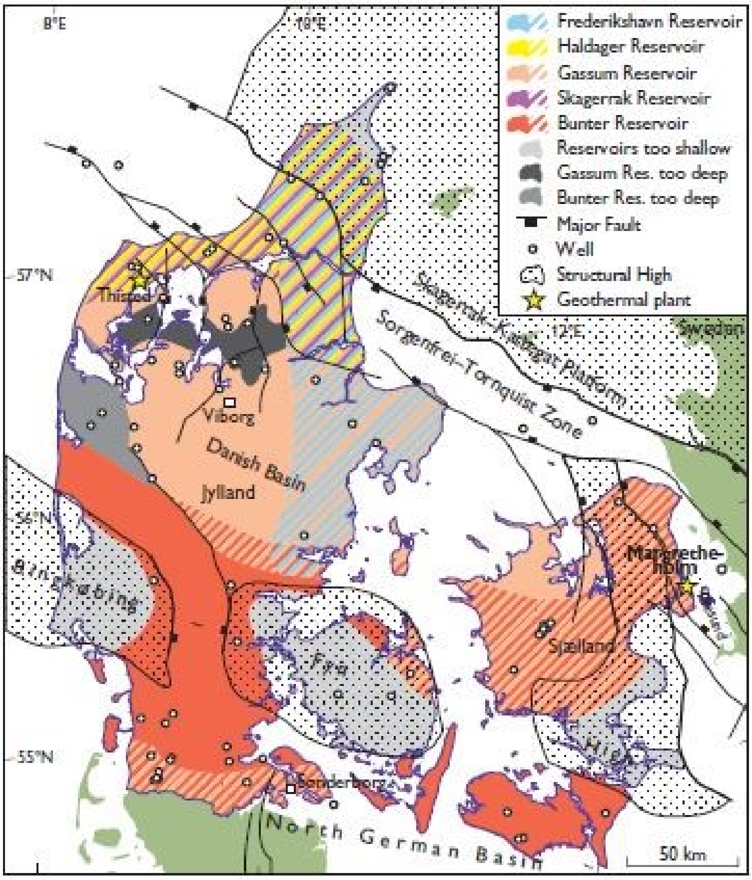

FIGURE 4: Geothermal reservoirs in Denmark (Røgen et al., 2015)

Denmark has moderate geothermal temperature gradients and utilization of geothermal resources will be mainly for district heating, possibly supplying more than 60% of Danish houses. Danish aquifers have not been found suitable for power production but a study conducted in 2010 has assessed the reserves in a licence for the Greater Copenhagen area to be 60,000 PJ, or 1/3 of the heat demand for about 5000 years. Today Denmark has three geothermal plants with deep wells (Mahler et al., 2013).

The first of them started production in Thisted, in 1984, and later expanded to produce up to 7 MWth from a flow of 55 L/s at 44°C from the Gassum sandstone reservoir. In 2005 production started in the second geothermal plant, located in Copenhagen, for production of 14 MWth from 65 L/s 73°C, 19% saline, geothermal water from the Bunter sandstone reservoir at 2.6 km depth (Mahler et al., 2013). The latest geothermal plant, located in Sønderborg, started production of up to 12 MWth in 2013 from 48°C geothermal water produced from the Gassum reservoir at 1.2 km depth.

The geothermal reservoir exploited at Thisted is a Lower Jurassic Gassum formation sandstone at 1,250 m depth producing saline water at 43°C. The geothermal plant functions with two wells, as a doublet, one for production and one for injection, located 1.5 km apart. It produces heat from the sandstone reservoirs through heat exchangers and/or LiBr based absorption heat pumps, where the driving heat primarily comes from biomass boilers for heat and/or combined heat and power production (Røgen et al., 2015).

The geothermal plant located in Copenhagen was inaugurated in 2005, using 19% saline water at 74°C from a geothermal reservoir in the Lower Triassic Bunter Sandstone formation at 2.6 km depth. The production is from a deviated well and the injection is into a vertical well next to it at ground level, and 1.3 km apart at reservoir level. The injectivity of the injection well has increased over the years, reflected by increasing injection pressure, after an initial clean-up of the injection well. This is believed to be linked with low injection pressure and high injection temperature during summer plant shutdown periods (Røgen et al., 2015).

The injectivity has been increased by acidizing several times but the well completion with perforations carries a risk of perforation collapses. Acidizing of the well has not maintained a low injection pressure and an effort is put into studying and avoiding the issues, which are believed to have caused the high injection pressure (Røgen et al., 2015).

3.5 Poland

Poland is characterized by low-temperature geothermal systems encountered in sedimentary basins. The main geothermal regions in Poland are located in sedimentary formations and contain geothermal aquifers in the following areas: The Polish Lowland Province (Triassic – Cretaceous); the Fore-Carpathians (Mesozoic - Tertiary) and the Carpathians (Mesozoic – Tertiary). Poland is built of three geostructural units: Precambrian platform of Northwestern Europe, Palaeozoic structures of Central - Western Europe covered by the Permian - Mesozoic and Cainozoic sediments as well as the Carpathians (part of the Alpine system).

The heat flow values which can be found in sedimentary basin from Poland vary from 20 to 90 mW/m^2 and geothermal gradients vary from 1 to 4°C/100 m. The temperature encountered at the depths of 1 to 4 km may vary from 30 to 130°C, while the geothermal water flow can reach up to 150 L/s.

Geothermal utilisation in Poland is mainly related to space heating, bathing and balneology (Figure 5). In recent years geothermal utilisation has increased in the country with five new wells (two for production and three for exploration) drilled in the 2005-2009 period (Kepinska, 2010). The deep geothermal development was continued between 2010 and 2014, when thirteen new geothermal wells were drilled. Ten were drilled for exploration, of which one was unproductive, one for production, and two for injection and in addition one old well was deepened.

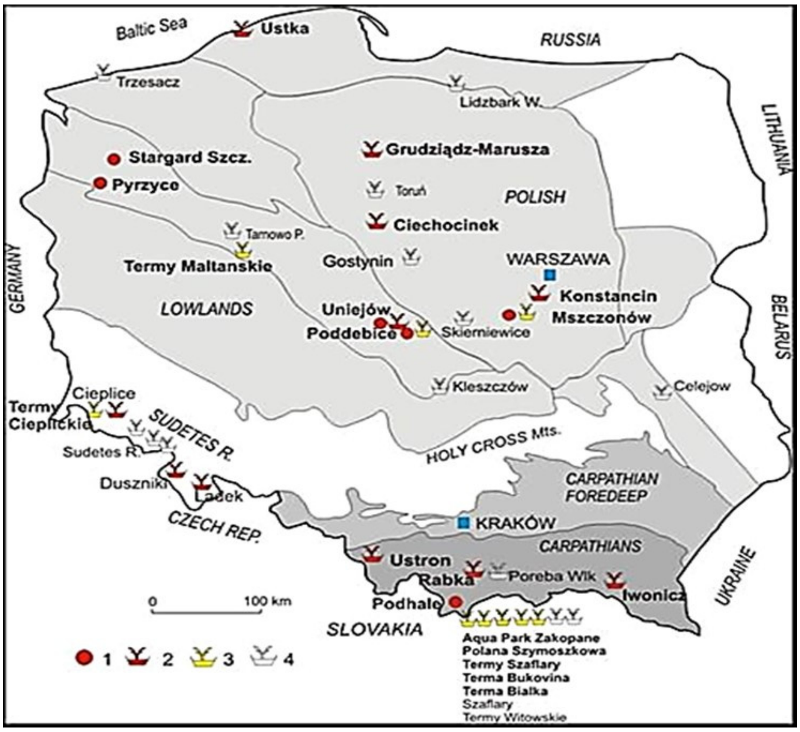

FIGURE 5: Main geothermal utilisation in Poland, 2014; 1) geothermal district heating plants, 2) health resorts; 3) recreation centres; and 4) geothermal recreation/ balneotherapy centres under construction (Kepinska, 2015)

In 2014, six district heating geothermal plants were found, in the Podhale region (since 1994), in Pyrzyce (since 1996), in Mszczonow (since 1999), in Uniejow (since 2001), in Stargard Szczecinski (since 2012, re-opened after closure in 2008), and in Poddebice (since 2013). In 2014, nine geothermal recreation centres and 11 geothermal health centers (balneotherapy) used geothermal water due to their therapeutic properties. Geothermal exploitation for district heating in Poland is mainly based on reinjecting return water back into the geothermal aquifers (Kepinska, 2015).

3.6 Slovenia

Slovenia is located in the convergent area of the African and Eurasian tectonic plates. The Slovenian area is subdivided into several tectonic units: the Mura-Zala basin (the southwestern part of the Pannonian basin) in the northeast part, while the Eastern Alps (incl. magmatic rock complexes), the Southern Alps, the External and Internal Dinarides and Adriatic foreland represent parts of the Adriatic microplate. The 24 thermal (natural and captured through shallow wells) springs have temperatures close to, or above, 20°C, with 36°C as a maximum. Geothermal resources of Slovenia are at present used only for direct use for space and district heating and for thermal spas, from 53 production wells and 3 thermal springs, implemented at 32 localities, shown in Figure 6, despite the hydrogeological characteristics of the northeastern part of the country indicating potential geothermal resources exploitable for electricity production.

FIGURE 6: Geothermal utilization in Slovenia (2013) (Rajver et al., 2015)

The geothermal studies performed in recent years reveal geothermal and hydrogeological conditions in the Mura-Zala sedimentary basin that can support the exploitation of thermal water from a Neogene aquifer at temperature of 80°C, at 2 km depth, east of Maribor and Ptuj towns. Upper Pannonian-Pontian geothermal sandy aquifers, utilized by Hungary and Slovenia, and composed of 50-300 m thick sand-prone units, are found in a depth interval of about 700-1400 m in the interior parts of the Pannonian basin, with temperatures from 50 to 70°C (Rajver et al., 2015).

There has been a discussion on reinjection in Slovenia because many localities in the northeast part of the country are vulnerable to over-exploitation due to utilization by different companies from the same aquifer. A doublet scheme is operational in downtown Lendava while the Murska Sobota community drilled two new wells, production well (SOB-3g/12, 1.5 km deep) and a reinjection well (SOB-4g/13, 1.2 km depth), for enlarging the district heating system in the northern part of the town. A test performed in 2013 revealed that the SOB-4g well can reach maximum flow rate of 43 L/s and wellhead temperature of 57°C. It is planned to use well SOB-4g as an injection well with a temperature drop of 30°C.

Projects T-JAM and TRANSENERGY, supported by the European Union, and conducted between 2009-2013, treated geothermal aquifers in the Mura-Zala basin as a transboundary resource between Hungary, Austria and Slovenia. As a result of these projects the geothermal maps of the region were updated and a sound hydrogeological conceptual model of the groundwater flow was developed. The negative trends of geothermal resources in different locations, and also negative trends at a regional level in north-eastern and eastern parts of Slovenia, must be managed for sustainable transboundary resource utilization, and doublet technology in the Pannonian basin is expected to provide best practices for sustainable utilization of the geothermal resources (Rajver et al., 2015).

3.7 Sweden

Sweden is characterized by the massive Baltic rock shield and its diverse crystalline eruptive and metamorphic rocks, whereas the southern part is characterized by sedimentary rock formations of significant thickness. The porous sandstone rocks found in the southern parts have very good hydraulic properties and also a geothermal gradient of 28-30°C/km, while the geothermal gradient is around 15-16°C/km in the Baltic shield regions.

Even though research for a deep geothermal project has been going on at Lund University since 1977, the lack of favourable geological conditions does not make Sweden suitable for deep geothermal exploitation (Gehlin et al., 2015).

The first geothermal plant in Sweden, which uses deep geothermal resources, started in 1984. It uses four production and five injection wells (Figure 7) for district heating the municipality of Lund, covering around 20% of the heat demand. The geothermal water is harnessed from sandstone reservoir located at a depth of 650-800 m, with a temperature of 21°C from production wells and injected back into reservoir at 5-7°C (Alm, 2011).

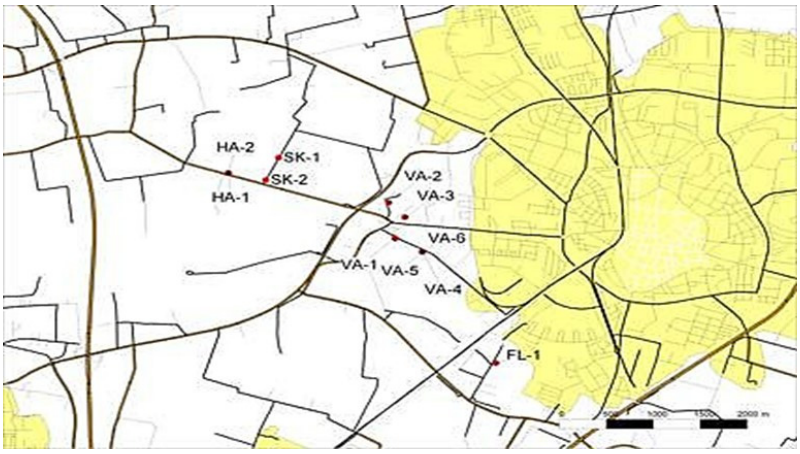

FIGURE 7: Production and injection wells in Lund in Sweden (Alm, 2011)

3.8 Germany

Geothermal utilisation of deep resources in Germany is related to the existence of natural geothermal systems (Figure 8) of three type of reservoirs (hot water aquifers, faults, and crystalline rocks) with temperatures above 100°C and at depths down to 7,000 m. Geothermal reservoirs are located in the North German Basin, the Upper Rhine Graben, and the South German Molasse Basin. Geothermal water from the North German Basin is characterized by high salinity and temperatures between 40 and 120°C, while the geothermal resources in the South German Molasse Basin are characterized by high temperature and low salinity. It is difficult to develop geothermal projects in large scale because of the characteristics represented by faults and heterogeneous geology of Upper Rhine Graben (Seibt et al., 2005, Weber et al., 2015).

The first production and injection tests in Germany were performed in 1982 in a sandstone reservoir in order to ensure the district heating for a residential area in the town of Waren (Muritz).

Sandstones reservoirs that can be found in the North German Basin at depths of around 3000 m have the following properties: effective porosity >20%, permeability > 0.5×10^{-12} m^2 and effective thickness > 20 m, indicating good conditions for injection purposes. As was mentioned above the Mesozoic deep waters contained in the North German Basin are classified as high salinity Na–(Ca–Mg)–Cl water (salinity greater than 300 g/L) with a high pH caused by dissolved gases. Injection of the cooled waters back into the reservoir can affect the permeability of the rocks, mainly because of excessively high injection and production flow rates, chemical incompatibility between injected fluid and reservoir aquifer, oxidation materials and bacterial activity. Due to these properties, special submersible pumps made of corrosion-resistant material have to be used (e.g., red bronze for the running wheels). The pipes used are made of coated or inert material for the same reason and to prevent eventual leakage into other aquifers, in particular groundwater-bearing beds with usable freshwater resources.

The first project which injected geothermal water after utilisation started in 1985 in order to supply heating in the town of Waren. Geothermal water is harnessed from an aquifer composed of Hettangian sandstones at a depth of 1470 m, providing flow rates of around 17 L/s at a temperature of 62°C. After utilisation the cooled water is successfully injected at temperatures of 20-40°C. The salt content of this NaCl brine is 158 g/L, and iron content is 12 mg/L.

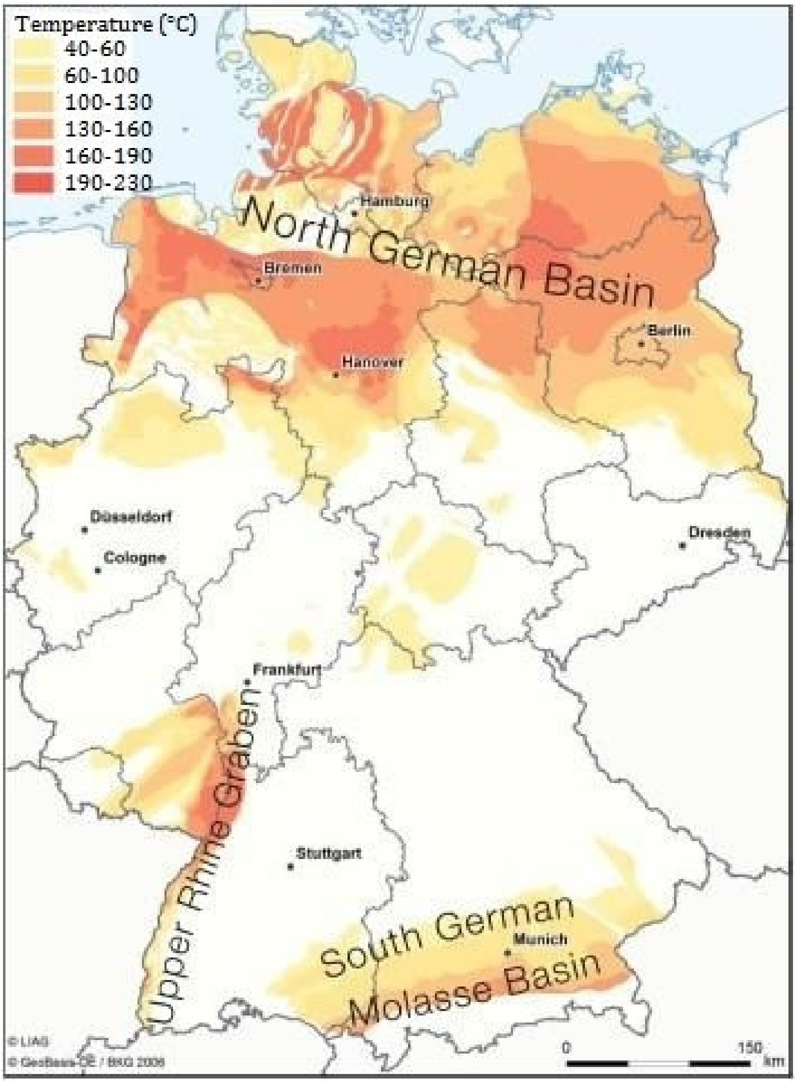

FIGURE 8: Geothermal resources in Germany (map adapted from Suchi et al., 2014, Weber et al., 2015)

The site of Neustadt-Glewe geothermal field was explored in 1989 and the power plant started operations in 1995. The properties of geothermal resources from this site are characterized by a temperature of 100°C, a high salinity content (salt content of 220 g/L) iron content of 80 mg/L and high gas concentration in the fluid. In 1998, the oxygen entered through a defective regulating valve over a short period of time causing iron precipitation, which made it necessary to increase the injection pressure. After acidizing operations the injectivity of the well was restored and geothermal water injected back into a sandstone layer at a depth of 2200 m with a maximum flow rates of 35 L/s.

Neubrandenburg geothermal plant was commissioned in 1989. Geothermal water is harnessed from two fine sandstone horizons located at depths of 1,150 and 1,250 m, with flow rates up to 28 L/s with a salt content of 113 and 133 g/L, respectively, and after utilisation the water is injected back into the aquifers. The injectivity deteriorated continuously until the plant was rehabilitated in the 1990s. This included the installation of a nitrogen pressurizing system. The geothermal plant was reactivated and retrofitted for combined use as geothermal plant and waste heat aquifer of a gas and steam cogeneration plant for producing brine for therapeutic purposes. A new thermal water loop was installed and it is planned to heat the thermal water up to 80°C by waste heat during summer operation and to inject it. This heat will be recovered during winter, therefore increasing the efficiency of the plant significantly (Seibt and Kellner, 2003).

3.9 France

Geothermal development in the Paris basin started in the early 1970s. Since then 55 doublet systems have been implemented, 34 are still in operation using the Dogger aquifer of the Paris Basin. The Paris Basin is a sedimentary basin which occupies a large part of Northern France (110,000 km^2) and extends northward below the English Channel. It is connected with the Aquitaine basin to the southwest with the "Poitou High" and the Southeast basin with the "Burgundy High". The existence of Paris Basin is related to a period of rifting in Permo-Triassic times. The central part of the Basin, where the subsidence was the greatest, is filled with about 3000 m of sediments. The Dogger strata were deposited in a marine environment and is recharged along the eastern border of the Paris Basin where the formation outcrops.

Fluid density, variations caused by different salinities or temperature gradients may induce local perturbations, but on a basin wide scale the flow is directed towards the discharge area on the seafloor of the English Channel, in the north-western part of the basin. In the recharge part, the fluid reaches depths of 2000 m where it acquires its geothermal potential. Between 1970 and 1985, 110 geothermal wells were drilled in the Paris Basin (Figure 9), targeting the Dogger aquifer, but 42 wells were abandoned for technical (corrosion and scaling) or economical (low profitability of geothermal plants compared with low price for fossil fuels) reasons. As was mentioned above, 55 doublets were in operation in the 1980s, but just 34 of these are still exploiting the Dogger aquifer. Twenty-nine geothermal plants are used for district heating, by exploiting the Dogger Aquifer (1,600-1,900 m depths) with fluid temperatures above 65°C. Each plant uses one or more doublets and a few of them have been using triplets (three wells, one new well drilled for production and the existing wells used for injection). Abandoned wells are located in the northwest part of the basin, where the geothermal water reaches 60–65°C or less (Lopez et al., 2010, Vernier et al., 2015).

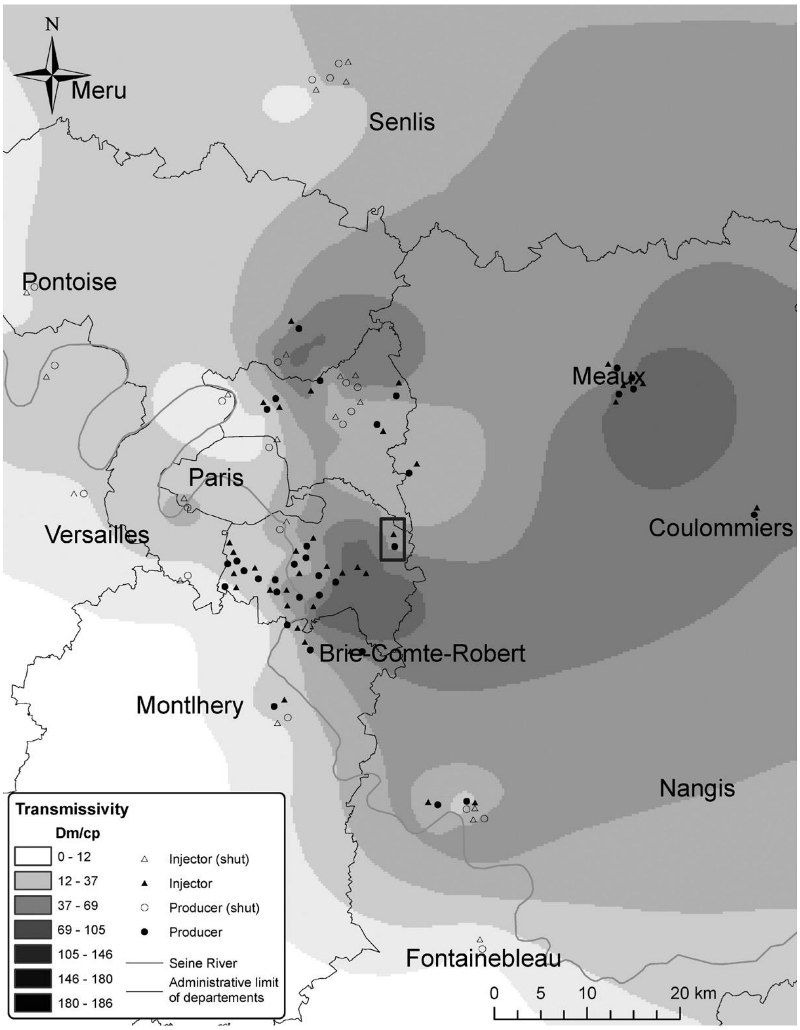

FIGURE 9: Temperature map and geothermal well locations in the Paris Basin; the grey rectangle highlights the Champigny doublet (Rojas et al., 1989)

Some new geothermal plants for heating have been commissioned since 2007 in the Paris basin. Orly Parisian airport now uses the heat produced by a new doublet developed by ADP in order to ensure heat demand for the airport. Strategies for rehabilitation of old wells involve the following: some doublets are transformed into a triplet, as in Champigny-sur-Marne, a new production well has been drilled and both the existing wells are used for injection, some doublets are closed, while a new doublet was drilled in the vicinity (e.g. in Coulommiers) in a case where wells were damaged.

In order to prevent conflicts of use from the Dogger aquifer, the data on running operations is collected by BRGM and thermo-hydraulic modelling of the aquifer is conducted to show where new wells can be drilled. In addition, some operations are carried out in the intermediate aquifers of the Paris basin, one doublet which uses geothermal water from the Albian aquifer (650 m depth), for district heating in Issy-les-Moulineaux. This doublet provides a temperature of 28°C and a flowrate of 55 L/s, giving a thermal capacity of 5.4 MWth for heating and 1.3 MWth for hot sanitary water. Another doublet has been realized in the Neocomian aquifer (900 m depth, 34°C temperature), which provides heat for 3,500 social households in Plessis-Robinson, close to Paris (Vernier et al., 2015).

3.10 Hungary

The main utilisation of geothermal energy in Hungary is based on utilizing resources in the Pannonian basin (Carpathian Basin). The main reservoirs with geothermal resources are in Mesozoic carbonate-karstic basement rocks and the Pliocene – Upper Pannonian porous sedimentary layers, with medium temperature of water between 30 to 100°C. Pannonian sediments are multi-layered, composed of sandy, shale and silty beds with different permeability. The lower Pannonian sediments are mostly impermeable; the upper Pannonian and Quaternary formations contain porous layers of permeable sand and sandstone. The upper Pannonian aquifer has an area of 40,000 km^2, an average thickness of 200-300 m, a bulk porosity of 20-30% and a permeability of 500-1,500 mD. In 2014, 672 wells (179 wells abandoned and 220 temporarily closed) in Hungary could produce geothermal water with a temperature of more than 30°C (Toth, 2015).

A high-enthalpy reservoir with over-pressured steam and a temperature of 189°C has been drilled into in the south-eastern part of the country. This reservoir was discovered in 1985 in the Fabiansebestyen exploratory well when over-pressured steam at 360 bar was discharged at around 100 L/s, from a 3,800 m deep reservoir in a fractured dolomite formation. The well was killed after 47 days and at present, feasibility studies are being carried out in order to determine the geothermal potential for this area.

The Miskolc-Mályi project (installed capacity of 21 MWth) is a recent project which uses geothermal water for district heating. The geothermal plant uses two wells for production drilled to a depth of 2,305 m and 1,514 m, yielding 110-150 L/s of fluid with a temperature between 90 and 105°C from a karstified-fractured Triassic limestone reservoir. At Miskolc-Mályi three geothermal wells were drilled, also for injection purposes (Toth, 2015).

For balneology and sport purposes, Hungary uses around 295 thermal wells and 132 natural springs, with outflow temperature between 30 and 50°C. These wells mostly discharge from the Miocene porous sandstone reservoirs between an average depth of 500-1500 m. For agricultural utilisation in Hungary 181 geothermal wells are used providing heating for over 70 ha greenhouses and 250 ha of soil-heated plastic tents. Hódmezővásárhely is another city where the water used has been injected back into sedimentary reservoir for the last 60 years, without problems. Since 1969, geothermal water has been used in secondary oil production technology in the Algyő oilfield. At present 5,400 m^3/s of hot water are injected into the oil reservoir for oil displacement. Problems occur in the Hungarian sandstone aquifer when the pressure decreases in the reservoir when the fields have been exploited for a long time. One case is represented by Hajdúszoboszló field, where the piezometric head of the reservoir has subsided almost 70 m and the production can just be sustained by artificial lifting. Even though 672 geothermal wells have been drilled in Hungary, only 34 wells are (partly) used as injection wells. Efforts are being made in order to develop sustainable projects using geothermal energy. Due to this, from 2010 to 2014, four injection wells were drilled and the number of these is expected to increase in the future (Toth, 2015).

4. GEOTHERMAL ENERGY IN ROMANIA

4.1 Geothermal potential in Romania

The geothermal potential in Romania is associated with low-temperature geothermal systems, located in porous permeable formations such as the Pannonian sandstone, and siltstones specific for the Western Plain and for Olt Valley, or in fractured carbonate formations specific for the Oradea, Bors and North Bucharest (Otopeni) areas. The first well for geothermal utilisation in Romania was drilled in 1885 to a depth of 51 m, yielding water of 49°C. The maximum flow rate of this well is 195 L/s but it was never used with this flow rate. This well is located at Felix Spa, close to the municipality of Oradea, and is still in operation. It was followed by three additional wells; one drilled in 1893 at Caciulata with water at temperature of 37°C, one in 1897 at Oradea with water at temperature of 29°C and one in Timisoara in 1902 with water at temperature of 31°C (Rosca et al., 2005).

As part of a geological programme for hydrocarbon resource exploration from the 1960s geothermal research, aimed at using geothermal resources on a large scale, began. Since then, over 250 wells have been drilled with a depth range of 800-3,500 m, through which were discovered low-enthalpy geothermal resources with a temperature between 40 and 120°C. Most of them are located in the western part of Romania, while three wells are located in the southern part of the country. A recent study conducted by University of Oradea and S.C. Transgex S.A. identified 223 wells drilled after 1965. Over 80% of the wells are artesian producers, 68 of them were drilled in the Pannonian basin and require anti-scaling treatment, and four are injection wells. The total installed geothermal capacity in Romania is around 480 MWth for existing wells, at a reference temperature of 25°C. Currently, only about 200 MWth are used from 96 production wells with a temperature in the range of 40-120°C.

In Romania, around 40 wells are used for health and recreational bathing in 16 spas, most of them in the western part. According to the data presented in a country update for 2005-2009 regarding geothermal energy in Romania (Rosca et al., 2010), seven geothermal wells have been drilled to depths ranging from 1,500 m to 2,800 m. Three were unsuccessful (dry or cold), three are producing geothermal water with wellhead temperatures of about 70°C and the drilling of one started in late 2008. This well was planned to be drilled to at around 3,000 m depth. At 1,700 m, due to circulation losses, the well was completed and tested (without acidizing). It produced (in artesian discharge) about 10 L/s of geothermal water with about 90°C wellhead temperature (Rosca et al., 2010).

Between 2010-2016 (October), two geothermal wells were drilled to a depth of 2,500 m and 3,100 m, respectively, producing geothermal water with a wellhead temperature in the range of 80-90°C. Two more wells were drilled during this period for injection purposes. The first injection well from this period was completed in 2010 in the town of Beius (Bendea et al., 2015), and the second well, which is located in the municipality of Oradea (financed under the RO 06 Renewable Energy Programme through the EEA Grants Financial Mechanism 2009-2014), will be completed this year (2016).

As mentioned above, the geothermal systems of Romania (Figure 10) are found in the porous and permeable sandstones of the Pannonian basin, along the western border of Romania, interbedded with clays and shales specific for the Western Plain, or in carbonate formations of Triassic age in the basement of the Pannonian basin, and of Malm-Aptian age in the Moesian Platform.

In the western part of Romania the following geothermal reservoirs are known: Pannonian aquifer Oradea reservoir, Bors reservoir, Beius reservoir and Ciumeghiu reservoir. In the central and south part of the country the following reservoirs have been discovered: Cozia–Calimanesti reservoir (central) and North Bucharest reservoir (south).

The Pannonian geothermal aquifer is multi-layered, confined and is located in the sandstones at the basement of the Upper Pannonian (late Neocene age), with an approximate area of 2,500 km^2 along the western border of Romania. The main geothermal areas are, from north to south: Satu Mare, Tasnad,

FIGURE 10: Location of the main geothermal reservoirs in Romania
(Bendea et al., 2015)

Acas, Marghita, Sacuieni, Salonta, Curtici-Macea-Dorobanti, Nadlac, Lovrin, Tomnatic, Sannicolau Mare, Jimbolia and Timisoara. The Pannonian aquifer has been explored by over 100 geothermal wells and currently 33 (mainly artesian) of them are exploited. This aquifer is encountered in the depth range of 800-2,400 m and the thermal gradient is 45-55°C/km. The geothermal water exploited is of sodium bicarbonate-chloride type, with a mineralisation (TDS) of 4-5 g/L and wellhead temperatures between 50 and 85°C. Due to this mineralization, most of the water shows carbonate scaling, prevented by downhole chemical inhibition. Utilisation of geothermal water in this areas is mainly for district heating (around 2,500 flats), sanitary hot water supply for 2,200 flats, greenhouse heating, covering 10 ha., health and recreational bathing, and fish farming.

The Oradea geothermal reservoir covers around 75 km^2 and is located in the Triassic limestone and dolomites at depths of 2,200-3,200 m. The reservoir is exploited by 14 geothermal wells with a total maximum artesian flow rate of 140 L/s with wellhead temperatures ranging from 70 to 105°C. The water is of calcium-sulphate-bicarbonate type with mineralization ranging from 0.9-1.2 g/L, without dissolved gases. The Oradea Triassic aquifer is hydrodynamically connected to the Felix Spa Cretaceous aquifer, and together they are part of the active natural flow of water. The water is about 20,000 years old and the recharge area is in the northern edge of the Padurea Craiului Mountains and the Borod Basin. Despite the fact that natural recharge of the geothermal system is significant for this reservoir, the exploitation with a total flow rate of over 300 L/s has generated a pressure draw down in the reservoir that is counteracted by reinjection of water into reservoir after utilisation. The first successful doublet started operation in 1992, in the Nufarul district, located near the south east corner of Oradea City. This doublet harnesses geothermal water from the Oradea reservoir for heat suppling 3,000 flats for 8,000 people (Bendea et al., 2015).

A new geothermal heating plant has been operating since 2005 in the Iosia district in the same city. The geothermal plant can supply 80% of the heat demand (at the design value of -15°C for outside temperature) and 100% for house tap water. The peak load for space heating is supplied by two natural gas fired boilers, which increase the supply temperature of the secondary fluid from 102 to 110°C. In 2012, a 50 kWe demonstration ORC power plant was installed to complete the heating plant, being the first operational geothermal electric generation plant in Romania (GEODH, 2016). The Felix Spa reservoir is at present exploited by over ten wells, drilled to depths between 50 and 450 m. The total flow rate available from these wells is 210 L/s, with wellhead temperatures of 36-48°C.

In the municipality of Oradea, the annual utilisation of geothermal energy is around 30% of the total geothermal energy produced in Romania (Bendea et al., 2015). Currently the municipality of Oradea is implementing a project for geothermal reinjection, with a final project date of 30.04.2017, financed under the RO06 Renewable Energy Programme developed by the Environment Fund Administration, through the EEA Grants Financial Mechanism 2009-2014. The well will be drilled to a depth of 2900 m and is expected to accept a flow rate of 45 L/s (Oradea, 2016).

The Bors geothermal reservoir is located at around 6 km north-west of Oradea and despite being located in fissured carbonate formations like the Oradea geothermal reservoir, these geothermal reservoirs are different. The Bors reservoir is a tectonically closed aquifer, covering a surface area of 12 km^2. The geothermal water contained in this reservoir has a mineralization of 13 g/L of dissolved salts, dissolved gases of 70% CO_2 and 30% CH_4 and high scaling potential, prevented by chemical inhibition. The reservoir temperature in Bors is over 130°C at depth of 2,500 m. The dissolved gasses are partially separated at 7 bars, which is the operating pressure, and then the fluid is passed through heat exchangers before being reinjected. The artesian production of the wells could only be maintained by reinjecting the whole amount of extracted geothermal water, and of colder water from shallower wells during the summer. In the past, three wells were used to produce a total flow rate of 50 L/s, and two other wells were used for injection, at a pressure that did not exceed 6 bar. Geothermal water from this reservoir has been used for greenhouse heating covering 12 ha., though with operations stopped for some time. In 2014, S.C. Transgex S.A. restarted the production from one well to supply heat to two companies in the area (about 17 TJ/yr).

The Beius geothermal reservoir is located about 60 km south-east of Oradea, in fissured Triassic calcite and dolomite at a depth range between 1,870-2,370 m. The first well was drilled in 1996 to 2,576 m depth. A line shaft pump was put in the well in 1999, now producing up to 45 L/s with a wellhead temperature of 83°C. A second well was drilled in early 2004, and a line shaft pump was installed later that year. This well can also produce up to 45 L/s geothermal water with an 85°C wellhead temperature. A third well was drilled in 2010 and is used to reinject the heat depleted geothermal water from the closed-loop systems. The geothermal water from the two production wells has low mineralization (462 mg/L TDS), and 22.1 mg/L non-condensable gases (NCG), mainly CO_2 and 0.01 mg/L of H_2S. The geothermal water from both wells is currently used to supply district heating to a large part of the town of Beius.

The Ciumeghiu geothermal reservoir is located in the Western Plain, about 50 km south to Oradea. The aquifer is located in Lower Pannonian age gritstone, at an average depth of 2,200 m. The geothermal water has a wellhead temperature of 105°C and high mineralization (5-6 g/L TDS), with strong carbonate scaling potential (prevented by chemical inhibition at the depth of 400 m). The main dissolved gas is CH_4. The reservoir was explored by four wells, but only one has been in use (as the greenhouses in the area have been closed).

The Cozia-Calimanesti geothermal reservoir (Olt Valley) is located in fissured siltstones of Senonian age. The reservoir depth is 2,700-3,250 m, the wells produce geothermal water with flow rates between 8.5 and 22 L/s, wellhead temperatures of 70-95°C and TDS of 15.7 g/L, without major scaling (only minor deposition and some corrosion). Despite the fact that the reservoir has been exploited for more than 25 years, there is no interference between the wells and no significant pressure draw down. The thermal potential possible to achieve from the four wells is about 14 MWth (of which 3.5 MWth are from the combustible gases – if used), but only about 7 MWth are used at present. The geothermal water is mainly used for district heating (2,250 equivalent flats), and for health and recreational bathing (Bendea et al., 2015).

The Otopeni reservoir near Bucharest will be described in the next chapter.

In Romania the main direct uses of geothermal heat are: district heating and individual space heating, health and recreational bathing, greenhouse heating (about 10 ha.), fish farming (a few farms), industrial processes, and drying. Detailed data on installed capacity and annual energy used is not available by type of utilisation. In areas where the available wellhead temperature is rather low, geothermal water is only used for health and recreational bathing (e.g. Felix spa), or for fish farming. In other areas, even where the temperature is higher, the geothermal water is still used only for bathing (e.g. Acas-Beltiug and Tasnad), or for fish farming (e.g. Santandrei). In larger communities where wellhead temperatures of the wells are higher, the geothermal water is first used for district heating, some industrial processes, with only a part of the heat depleted water used for bathing (or for fish farming), the rest being reinjected.

As a summary of the information presented above Table 3 shows comparative characteristics of the main geothermal aquifer in Romania.

TABLE 3: Characteristics of the main geothermal aquifer in Romania
(Rosca et al., 2005; Bendea et al., 2015)

Parameters	**U/M**	**Oradea**	**Bors**	**Beius**	**Western Plain**	**Olt Valley**	**North Bucharest**
Type of reservoir		carbonate	carbonate	carbonate	sandstone	gritstone	carbonate
Area	km^2	7	12	47	2,500	10	300
Depth	km	2.2 - 3.2	2.4 - 2.8	2.4 - 2.8	0.8 - 2.1	2.1 - 2.4	2.0 - 3.2
Drilled wells	Total	15	6	3	88	4	18
Well head temperat.	°C	70 - 105	120	84	50 - 90	70 - 95	51-84
Temperature gradient	°C/100 m	3.5- 4.3	4.5-5.0	3.3	3.75-4.15	3.0-3.5	2.3 - 2.6
TDS	g/L	0.8 - 1.4	12 -14	0.46	2 - 6	15.7	2.2
Exploitable reserves (for 20 years)	MW/day	570	110	52	4,700	300	840
Flow rate	L/s	4 - 20	10 - 15	4 - 12	4 - 18	12 - 25	22 - 28
Type of production		artesian	artesian	pumping	artesian+ pumping	artesian	pumping
Total installed power (with existing wells)	MW$_t$	58	25	10	12.5	18	35

Exploitation of shallow geothermal resources in Romania started in the 1990s with ground source heat pumps (GSHP) applications, with ground water wells preferred instead of horizontal heat exchangers. Currently in Romania, GSHP applications are not regulated by technical rules and therefore it is impossible to obtain data from all companies which are installing and utilizing such systems. No specific authority or institute has especially been appointed to collect data/information, to certify, authorize and monitor the performance of these applications, which result in the lack of reliable data for these applications. Table 4 shows the total length of the largest GSHP systems, with borehole exchangers longer than 10,000 m, built in Romania.

Since 2010, the Romanian Government has supported the utilization of renewable energy sources, including ground source heat pumps, for new systems installed by individuals. Because the Government did not allocate the necessary funds in 2014 to continue the program, the geothermal heat pump market dropped to about half. Based on available data, the heat capacity of the ground source heat pumps installed in Romania by the end of 2014 is estimated at about 40 MWth.

TABLE 4: Largest GSHP systems with borehole heat exchanger in Romania (Bendea et al., 2015).

City – beneficiary name	No. of BHE	Depth BHE [m]	Total BHE [m]
Magurele – Bucharest, ELI-NP (under construct.)	1,080	125	13,500
Valul lui Traian, Cardinal Motors (2009)	357	70	24,990
Snagov, Vila 23 Hotel (2008)	224	70	15,680
Focsani, ARTIFEX (2012)	120	125	15,000
Bucharest, Midocar Est (2008)	144	75	10,800
Bucharest, Green City Hall (under construction)	80	125	10,000

The Romanian Geoexchange Society is a non-governmental organisation established in 2002 aiming to promote the HVAC GSHP systems, create a national regulatory framework, educate the users and direct them to RES, represent the Romanian market abroad, train Romanian specialists as well as contribute at the European training and certification frame.

During 2009-2014, the investment and employment in geothermal projects in Romania totalled about 5.7 million EUR, less than in any 5 year interval before. This was mainly from the State Budget, intended for drilling (field development). Out of the total investments in common geothermal projects, the cost of drilling the two wells needed, represents about 70% of the total capital cost. Successful wells can be leased from the National Agency for Mineral Resources, usually by the company that drilled them (Bendea et al., 2015).

Approximately additional 6.4 million EUR, for investments in geothermal projects (drilling new well, research and development) in the current period, are supported by the RO06 Renewable Energy Programme, financed through the State Budget (15%) and the EEA Grants Financial Mechanism 2009-2014 (85%) (RONDINE, 2016).

4.2 Geothermal utilization in Balotesti area (Ilfov County)

Balotesti is an administrative territorial unit located in the northern part of Ilfov County, around 20 km away from Bucharest. It is neighboured by Snagov to the north, Otopeni to the south, Moara Vlasiei to the east, Corbeanca to the south-west, Peris to the north-west and Stefanestii de Jos to the south-east. Balotesti Commune has an area of 53 km^2 and it consist of three villages: Balotesti, Saftica and Dumbraveni. According to data from the National Institute of Statistics, in 2011, Balotesti Commune has a total population of 8314 inhabitants (Ilfov-Insse, 2016).

The geothermal utilisation in Balotesti area is based on the Otopeni geothermal reservoir, located in the northern part of Bucharest. The Otopeni, or North Bucharest, geothermal reservoir is partially delimited (about 300 km^2), with aquifers in fissured limestone and dolomites (carbonate rocks) at depth range of 2,000-3,200 m, belonging to the Moesian Platform. In this reservoir, through time, 24 wells have been drilled (of which only 18 are potential producers or injectors) demonstrating an important geothermal aquifer (Bendea et al., 2015).

Production has been carried out in the Otopeni area using downhole pumps, because the water level in the wells is at 80 m below surface. Geothermal water is exploited with a well flow rates between 22 and 28 L/s, a wellhead temperature of 58-84°C, and a rather high TDS (1.5-2.2 g/l) as well as a high H_2S content (up to 30 ppm). Here, it is recommended to inject the water after use into reservoir for environmental protection (Bendea et al., 2015). In the near future, three wells will be used in this northern area, one of these being drilled this year (2016) for recreational purposes. One of the other two wells (old wells) is used almost all the year for health and recreational bathing and another well will be used for district heating and domestic hot water supply for an emergency hospital. Through several wells drilled between 1981 and 1994, a high capacity geothermal reservoir has been discovered with a flow rate range of 20-60 L/s and wellhead temperatures of: 66°C near Otopeni airport, 76°C at Moara Vlasiei, 80°C north of Balotesti and 83°C at Snagov.

Three wells have been drilled in the Balotesti north area focused on geothermal research, named wells 2669, 2684 and 2685. Well 2669 was drilled between 1989 and 1991 to a depth of 3304 m, with production samples showing satisfactory results. Well 2684 was drilled north of Balotesti between 1995 and 1998 to a depth of 3052 m with better results in terms of thermal power capacity. Well 2685 was drilled as an injection well north of Balotesti between 1998 and 1999 to a depth of 3002 m. The production tests yielded unsatisfactory result regarding injectivity. Of these three wells, currently well 2684 has been rehabilitated and will be used for district heating and domestic hot water supply for a local hospital. According to existing data from the National Agency for Mineral Resources construction of well 2684 was performed as shown in Table 5.

TABLE 5: Design of well 2684 at Balotesti

Well	**Depth (m)**	**Diameter casing (″) /cased interval (m)**					**Open hole interval (m)**	**Cemented interval (m)**
		20	**13 $^{3/8}$**	**9 $^{5/8}$**	**7**	**6 $^{5/8}$**		
2684	3052	-	0-1140	642-2230	-	1.639-2318.7	2318.7-3052	0 – 2318.7

After drilling, well 2684 in Balotesti was tested in the depth range of 3052-2318.7 m (open hole). Concentric air-lift pump was used to stabilize temperature, flow and dynamic level. The results are as follows: flow rate of 20 L/s, dynamic fluid level at 87 m, static fluid level at 65 m and wellhead temperature in the range of 82-84°C. These wells were drilled as a part of a geothermal research programme and following the testing the governmental agencies responsible decided to cement the wells in order to preserve them.

From 2014, the administrative territorial unit of Ilfov County Council started a project in order to harness geothermal water from well 2684 for district heating and domestic hot water supply for an emergency hospital located in north Balotesti, close to well 2684. The project is financed under the RO 06 Renewable Energy Programme developed by the Environment Fund Administration as programme operator, through the EEA Grants Financial Mechanism 2009-2014 (RONDINE 2016). The project has a grant of around 1.7 million EUR for eligible costs and is planned to be completed in 2016, by starting operations. The project involves construction of a geothermal plant, which will use the geothermal water produced by well 2684 for heat and hot water supply. The geothermal plant will replace the current plant that uses gas for heating and hot water. Realization of this project will include rehabilitation and testing of well 2684, geothermal installations (consisting of an uncovered storage tank with a capacity of 500 m^3, well 2684 fully equipped and a geothermal station), pipe-line for used geothermal water, round trip circuit for heat and hot water, distribution network and connection to the consumers. The completion of this project aims at ensuring sustainable energy development while protecting the environment. According to recent data (2013) the annual number of beneficiaries of this investment will be around 11,000 persons (Hidroservices, 2014).

This year (2016) a new well to a depth of 3107 m has been drilled in the same area of Balotesti. This well will exploit geothermal water in order to supply water for a new spa (private investment) built in Balotesti. According to the production test performed this year, the new well yielded hot water with a temperature of 81-82°C and a flow rate of around 25 L/s. The geothermal aquifer is exploited with a submersible pump of 48 kW with variable flow (frequency converter) placed at a depth of about 150 m, operable up to temperature of 90°C (AHGR, 2016).

4.3 Thermal breakthrough time in Balotesti area

The main detrimental effect due to reinjection is the cooling of a geothermal reservoir, and even of production wells. Although reinjection is not performed now in the Balotesti area, reinjection will be needed in the future, if the reservoir will be used mainly for district heating and hot water supply through a doublet (production-injection) scheme. Therefore, cooling may occur in the long term so it is necessary to estimate the long-term thermal breakthrough time for the field (North Bucharest-Otopeni reservoir).

For this area a simple porous model with an infinite, homogeneous, isotropic, fluid-saturated, hot (at temperature T_r), horizontal layer of porous material with porosity $\emptyset$ and thickness H, was used. At time $t = 0$, injection of cold (at temperature T_o, cold relative to the initially hot layer) water at a rate Q (kg/s) is initiated at the location $r = 0$ (location of the injection well) (Zheng, 2015). By assuming that heat transport by conduction is negligible compared to the advection heat transport, one can show that a cold front travels radially away from the reinjection well (two-dimensional flow). On the inside of the front, the temperature is T_o, while on the outside, the temperature is undisturbed at T_r. The distance to the cold front is then given as (Bödvarsson, 1972):

$$rT = \sqrt{\frac{\beta w Q t}{\pi H < \rho\beta >}} \tag{1}$$

where rT = Radial distance of cold front (m);
H = Reservoir thickness (m);
$<\rho\beta>$ = Average volumetric heat capacity of reservoir, or $\emptyset\, \beta_w\, \rho_w + (1-\emptyset)\, \beta_r\, \rho_r$ (J/m^3/°C);
β_w = Heat capacity of water (J/kg/°C);
ρ_w = Water density (kg/m^3);
$\emptyset$ = Rock porosity;
β_r = Heat capacity of rock (J/kg/°C);
ρ_r = Rock density (kg/m^3);
Q = Injection rate (kg/s).

Currently, according to the result of the production test carried out for the two production wells in the Balotesti area, the production flow rate ranges from 25 to 34 L/s with temperatures between 81 and 85°C. Assuming that the reservoir thickness is between 200 and 400 m and using three injections rates of 10, 15 and 25 kg/s we can estimate the distance that is needed between production and injection wells to avoid thermal breakthrough time. The breakthrough time is calculated as a function of the distance between production and injection wells.

The result of estimated cold front breakthrough time are presented in Figures 11 and 12. To avoid thermal breakthrough in 100 years, the estimated safe distance between the injection and reinjection wells should be more than 450 m for the case with a reservoir thickness of 200 m and more than 300 m for the case with a reservoir thickness of 400 m. The results of this model are optimistic, because in this model a homogeneous and isotropic system without fractures is assumed. In reality injection rates will be variable, not constant, and the active reservoir thickness may be quite different from what is assumed here.

Based on these results, it is recommended that the reinjection wells should be located at more than 450 m distance from the production wells in the Balotesti area. However, these results are uncertain because the reservoir thickness and other system parameters are quite poorly known. Once reinjection wells have been drilled, tracer tests should be conducted to estimate these parameters more accurately.

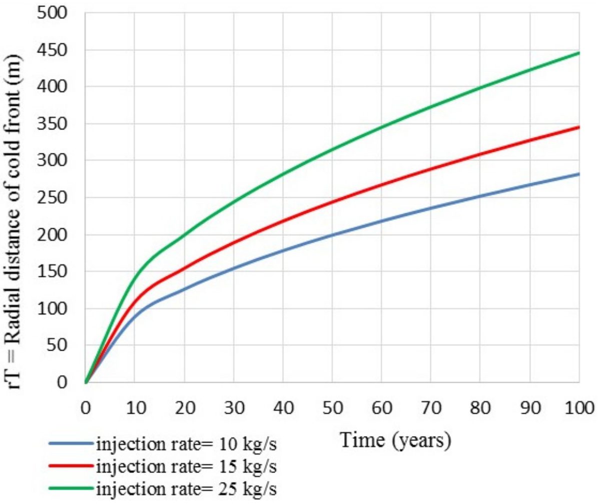

FIGURE 11: Estimated cold front breakthrough time for a reservoir thickness of 200 m with different reinjection rates in Balotesti area

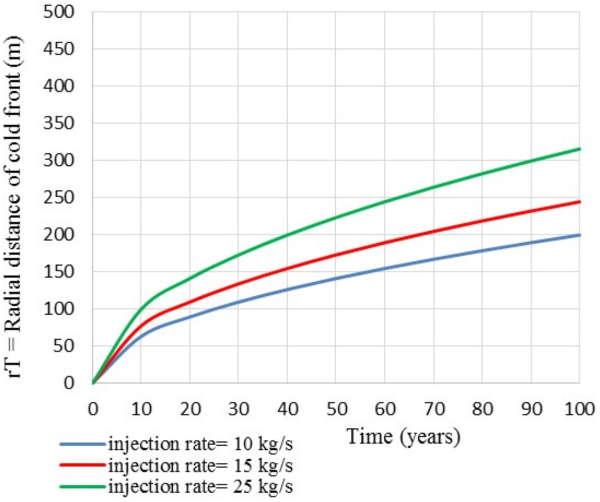

FIGURE 12: Estimated cold front breakthrough time for a reservoir thickness of 400 m with different reinjection rates in Balotesti area

4.4 Governing laws and development opportunities

Romania became a member of the European Union in 2007 and since then the Romanian legislation has been harmonized with the European Union legislation. Romania adopted and included in the Energy Strategy for 2007-2020, the European energy targets, to increase the share of renewable energy to at least 20% of the total consumption. By 2020, the EU aims to combat climate change and air pollution, decrease its dependence on foreign fossil fuels, and keep energy affordable for consumers and businesses. Even though Romania still uses fossil fuels for district heating and hot water supply, efforts to reach the European target are being made by the Romanian authorities. On this line, the Romanian government has launched national programmes in order to increase the renewable energy consumption, to reduce the emission of greenhouse gases and to reduce pollution. A part of these programs have been implemented from the State Budget, by the Environment Fund Administration, governmental agency under the Ministry of Environment, Waters and Forests. Also, the Environment Fund Administration, implemented the RO 06 Renewable Energy Programme with a total value of around 12 million EUR, financed by the State Budget (15%) and EEA Grant Financial Mechanism 2009-2014 (85%). The RO 06 Renewable Energy Programme supports two energy components, hydropower and geothermal, through which the utilisation of renewable energy resources will be increased (RONDINE, 2016; European Commission, 2016).

The Operational Programme Large Infrastructure has been developed in accordance with the identified development needs of Romania, through the Partnership Agreement 2014-2020, and in line with the Common Strategic Framework and the Position Paper of the European Commission services. To promote clean energy and energy efficiency, through the Operational Programme Large Infrastructure, Priority Axis 6 “Promote clean energy and energy efficiency in order to support a low-carbon economy”, Romania has allocated around 197 million EUR. Through the specific objective “Increasing production of less exploited renewable energy (biomass, biogas, geothermal)” of the axis mentioned above, territorial administrative units located in regions with geothermal energy will have the opportunity to develop projects for harnessing geothermal energy (MFE, 2016).

In Romania, geothermal resources are owned by the state and explored and exploited under a Mining Law license issued by the National Agency for Mineral Resources, which is required for exploration and exploitation. The drilling operations for underground production are subject to environmental evaluation except wells drilled to depths of less than 50 m. As they are classified as mineral resources in accordance with the Mining Law, data regarding geothermal resources from the deep aquifers are currently confidential and can only be accessed by accredited persons in accordance with the same law.

In the *Country update of 2010-2014 for geothermal energy in Romania*, presented at the World Geothermal Congress 2015 in Melbourne, Bendea et al. (2015) describe the utilisation of shallow geothermal with GSHP and also mention the fact that Romania does not have any institutions especially appointed to regulate, to keep a database, to certify, authorize and monitor the performances of ground source heat pump applications. Despite this fact, considerable information about implementation of ground source heat pump applications is available on the Romanian Geoexchange Society database (Geoexchange, 2016).

5. CONCLUSIONS

Utilization of geothermal systems on a large scale for district heating started worldwide during the 1970s, after the first oil crisis. The important development of geothermal projects, therefore, took place when the world passed through the oil crisis. In contrast the price of oil has continuously decreased during the last two years. Hence, it will be interesting to see how geothermal will develop in the following years.

Reinjection is an important part of any geothermal exploitation project and it may turn into a key factor in the success or failure of geothermal operations. Even though reinjection started as a method of waste water disposal, it has now become an important part of sustainable management of geothermal resources, mainly by providing additional recharge and maintaining reservoir pressure. Other benefits include environmental management, such as when the water has high content of salts, minerals, H_2S etc., as well as to minimize subsidence. Each field has a different response to reinjection but the reservoir permeability defines the connection between production and the injection areas. Selecting the distance from injection wells to production wells is a challenge when the geothermal reinjection system is designed.

Reinjection may cause difficulties and problems such as cooling of the production areas, high pressure required for water injection, groundwater contamination, increase of possible seismic activity in the area (induced seismicity) and changes in the water chemistry. Although reinjection is a part of modern geothermal exploitation, some countries do not yet require reinjection in their geothermal operations. This is at least partly due to the fact that geothermal projects which include reinjection require at least two wells from the start, one for production and another for injection, which will increase the initial project cost.

Countries such as France and Germany have now used geothermal water from sedimentary systems for district heating for several decades, utilizing geothermal systems consisting of production and injection wells in the same area. Throughout time, these countries have not encountered significant problems during exploitation. The principal exception is associated with injection into sandstone. But technical solutions have been developed for this problem in Germany and Denmark.

The European Commission set the three following key targets in order to ensure that the European Union meets its climate and energy targets for the year 2020:

- A 20% cut in greenhouse gas emissions (from 1990 levels);
- 20% of EU energy should come from renewables; and
- 20% improvement is expected in energy efficiency.

The 2030 climate and energy framework of EU sets three key targets for the year 2030:

- At least 40% cuts in greenhouse gas emissions (from 1990 levels);
- At least 27% share for renewable energy; and
- At least 27% improvement in energy efficiency.

Geothermal energy is a renewable and a nearly carbon free, form of energy available worldwide, which can be utilized in a sustainable manner and which can contribute significantly to the European Union being able to reach its energy targets for the year 2020 (European Union, 2016).

6. RECOMMENDATIONS FOR ROMANIA

Based on the examples of geothermal utilisation and reinjection in European countries, which harness geothermal resources from sedimentary basins, the following is recommended to support a considerable increase in the utilization of the geothermal resources in Romania as well as their sustainable management:

1. To maintain district heating systems as public property (may be partly privatized but municipality should remain the main owner).
2. Utilise reinjection wells for used geothermal water and use geothermal doublets (production and injection wells) in the district heating systems, with 100% reinjection, where possible.
3. Apply experience and technologies developed, mainly in Germany and Denmark, to maintain injectivity (by avoiding clogging) of sandstone reinjection wells.
4. Create a regulatory framework for ground source heat pump applications, especially when these applications use groundwater aquifers as energy source.
5. Appoint one institution to manage and apply the regulatory framework for GSHP, preferably an already existing institution which is involved in implementing renewable energy programs.
6. Open access to existing data that can be used for studying and assessing geothermal resources (i.e. use different classification than for mineral resources).
7. Increase fund allocation for geothermal research.
8. Increase geothermal utilisation to replace biomass, as a solution for a low-carbon emission and low environment impact.
9. Develop annual programmes for exploration drilling as a part of the state energy plan.
10. Develop annual programmes for ground source heat pump applications.
11. Include geothermal utilisation in regional development strategies.
12. Take into consideration ground source heat pumps applications as an energy source in feasibility studies for new or rehabilitated buildings.
13. Reduce the number of the approval papers (permits) required in development of geothermal projects.
14. Identify, launch or create national and regional geothermal programmes of cooperation between municipalities to implement integrated geothermal projects (district heating systems).
15. Set up a national network (with universities, research institutes, governmental agencies, non-governmental organisations, municipalities, private companies) to share data, analysis and studies for geothermal development projects.

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