Danube Transnational Programme
DARLINGe

REINJECTION
OF THERMAL WATER

WHY IS IT IMPORTANT?

Geothermal energy is the heat energy stored in rocks and in vapours, or thermal water trapped in rock pores and fractures under the Earth's surface. It is worth considering that most heat (>80%) is stored in the reservoir rocks themselves, and it is only the remaining part (in the fluids) that can be extracted.

The prevailing, historical use of geothermal energy is based on the irreversible extraction of thermal water. After its heat content is used, the energy-depleted (cooled) waste thermal water is usually emitted to a surface recipient such as a lake, a river, or a channel. The possible consequences of such discharge can be:

- Salinisation – increased chemical load of the recipient surface waters
- Thermal pollution – increased thermal load of surface waters
- The increased chemical load of the atmosphere – in some cases methane and carbon-dioxide are emitted as free gases
- Depletion of geothermal resources – usually first reflected as a significant decrease of the water level and / or pressure in production wells, but sometimes indicated in changes in temperature and the chemical composition of thermal water
- Depletion of produced energy over time, given that most heat is stored in the rock and not in the water

Therefore, when only geothermal energy (heat) is needed for a certain project, many of these issues may be mitigated if closed-loop circuits are applied. Geothermal reinjection involves returning some, or even all, of the energy-depleted water back into the same, hydraulically-connected geothermal reservoir through a reinjection well.

When operating together, a production well and a reinjection well are referred to as a geothermal doublet.

AIMS OF REINJECTION

Nowadays, reinjection is considered to be a highly important management strategy for any sustainable and environment-friendly geothermal development. Furthermore, it may become the key factor in the success of energy production.

Reinjection is essential in regions where multiple communities, or users would like to have access to geothermal energy, while at the same time achieving a degree of equality in its distribution. On such a scale, operation without reinjection could create a lack of thermal water; this would result in a lack of heat and could eventually lead to conflicts among the several users.

Chemical and thermal pollution of a surface stream

Reinjection well in New Zealand

A summary of the purposes of reinjection includes the following:

- to dispose returned waste thermal water from direct applications in an environmentally-safe way (namely, the prevention of thermal and chemical pollution of surface waters)
- to provide an additional recharge to geothermal reservoirs: in effect supplementing the natural recharge in order to prevent depletion
- to counteract reservoir pressure decrease due to the mass extraction of the water, thus contributing to the prolongation of the lifetime of a project and improving its economic output
- to enhance heat extraction from the reservoir rocks (production capacity) by heat recovery along flow-paths from reinjection to production wells
- to ease surface subsidence if caused by water extraction
- to enhance or revitalize surface thermal features such as hot springs and fumaroles.

Thus, this is a method which can greatly improve the efficiency of geothermal energy production and increase the longevity of geothermal projects for decades. As such, geothermal energy resources can almost be regarded as **renewable**, and their exploitation as **sustainable**.

In some countries, reinjection is required by law as an essential element of geothermal heat production. However, in other countries – including those of the DARLINGe project – production from a single well is very common. Here, experience strongly indicates that reinjection should be applied more frequently to restrain the trend of regional depletion of geothermal reservoirs.

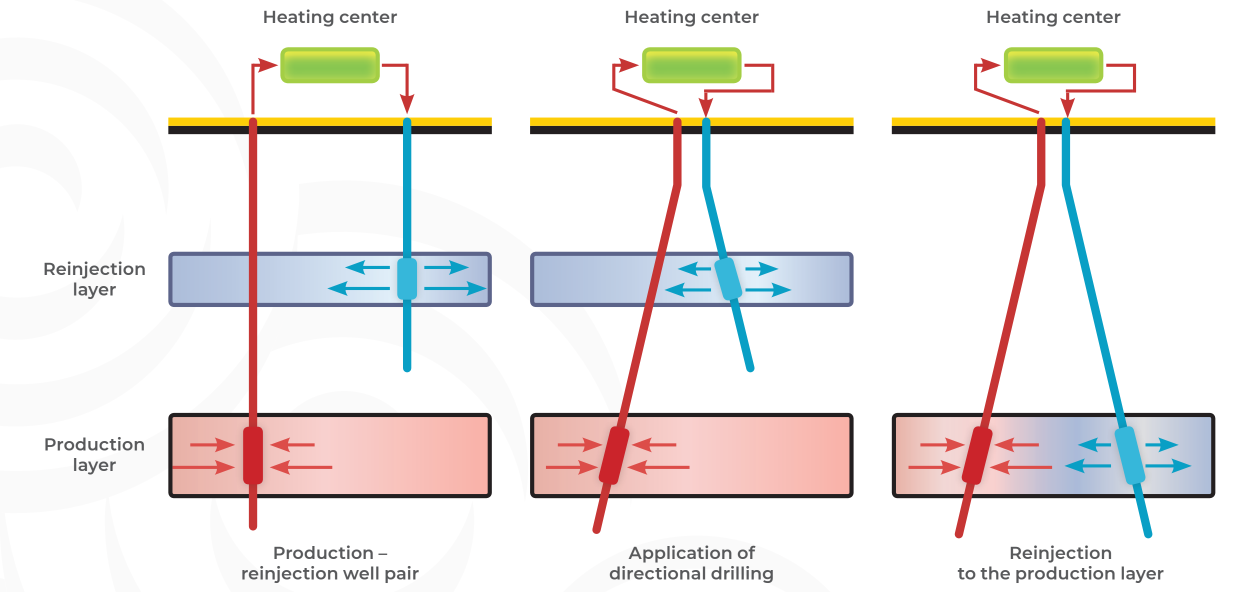
It is clear that reinjection wells represent a large part of the initial investment costs, and this is usually the main reason for not constructing them. Yet drilling and surface piping costs can be reduced – and some other factors for success optimised – when applying inclined or sub-horizontal wells. In such a manner, the wellheads of a production well and a reinjection well are placed as close together as possible, while their production and injection zones are as far away from each other as possible. However, attention must be paid to the fact that the proper construction of such wells is also much more demanding in comparison to single vertical production wells. This is especially true with respect to construction alongside loose sandstone and detrital sedimentary rocks, which are the main regional and transboundary geothermal aquifers in the Pannonian basin.

It can be pointed out that exploitation of geothermal resources does take place in some less vulnerable natural systems, and these work quite well without applying reinjection. However, in such cases, reservoir management is very strict and consists of targeted monitoring systems; these systems provide input information for numerical models which refer to groundwater flow and heat transfer. In addition, there are other methods which can assess the balance of water and heat in the reservoir, as well as the balance between the natural recharge and discharge/production rates at diverse production scenarios. In such case, the extraction of fluid is limited so that it does not have an irreversible affect on the balance of water and heat.

Any successful management of geothermal reservoirs should consist of a combination of monitoring and modelling approaches. This makes it possible to assess the effects of thermal water production and reinjection scenarios in space and time.

GEOLOGICAL RISKS

With respect to geothermal developments, “geological risk” refers to all possible deviations from expected results due to the uncertainty behind the knowledge about the nature and structures of the subsurface rocks. This uncertainty might result in the discovery of an unexpected geological situation, which is totally unsuitable for the production of geothermal energy. Therefore, by increasing geological knowledge with the acquisition and assessment of high-quality



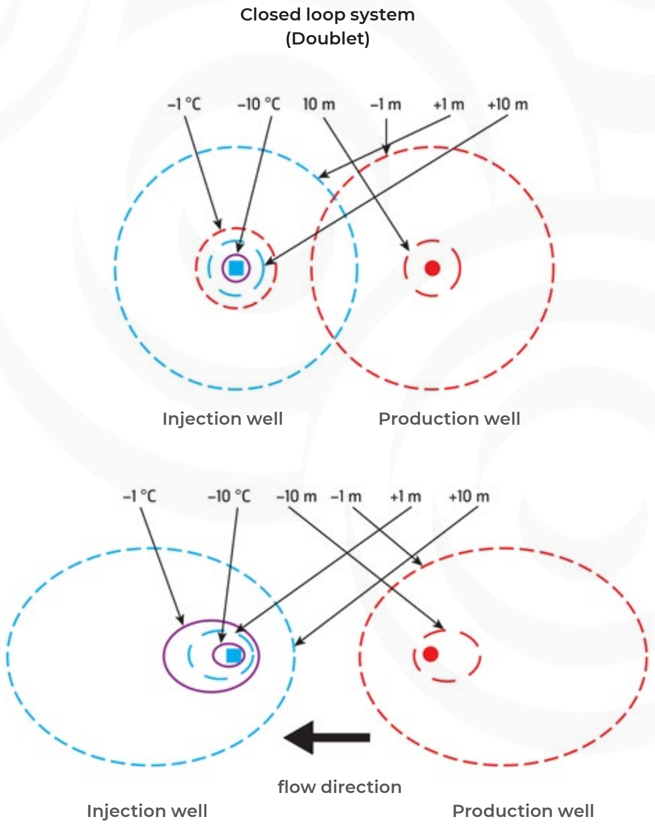
Vertical location possibilities of reinjection and production wells

geoscientific data, the risk of an inadequate evaluation of a site is reduced, and associated negative scenarios can be avoided.

There is a distinction between short-term and long-term risks. A short-term risk is, for example, the lack of economically sustainable geothermal resources – i.e. if the drilled target (reservoir) is not found, or if it is not permeable, then the well is not productive. Long-term risks may occur during the operation of an already established – otherwise successful – geothermal project.

The application of reinjection is the only long-term risk-mitigation measure which helps to avoid the pressure decline in the resource (reservoir depletion) on a large scale, and during long-term operation. It is a technical procedure which calls for high-quality well design, the completion of the well and its testing and operation, and close observation of the several risks involved. Risks on the reservoir scale are more probable at fractured reservoirs, while risks in the vicinity of the well (i.e. problems near to the well-bore itself) are more frequent at porous reservoirs.

Reinjection may be applied inside a production reservoir, on its periphery, above or below the producing layer, or outside the main production field; these different situations depend on the properties of the reservoir and its purposes. Whatever the case, there are risks attached to the verification of the adequate hydraulic connection between the production and reinjection wells prior to system operation. This connection should



The shape of hydraulic and thermal isolines under different flow conditions

be evaluated by *in situ* hydrogeological testing, including interference and tracer tests, and hydrogeological modelling.

For example, if the verification of the reservoir model is inaccurate, then the location of wells within a doublet may not be correct, thus eventually leading to a "breakthrough" of the thermal resource. Here, "breakthrough" refers to the time from the initial injection until the significant cooling of the water in the production well, so that the resource can no longer be economically used.

When placing several geothermal doublets in a reservoir, it is necessary to identify the zone affected by the hydraulic and thermal changes caused by production / reinjection; in this way the negative effects among the wells can be limited to a manageable level. Around a production well, hydraulic depression develops and reservoir temperature often increases, while increase of the reservoir pressure and cooling are abundant near the reinjection well. The threshold values of such zones are arbitrarily defined, usually depending on the utilization conditions. Furthermore, the spatial extent of these two zones is usually not the same, and they are usually smaller than the protection zone around the well; the latter is delineated on the bases of strict legal principles.

There are no simple, easy-transferrable solutions for the development of reinjection systems. Each site has unique advantages and challenges because of the respective geological settings. The latter should be sufficiently investigated before and during the operation of a system to ensure its long-term and cost-effective heat production.

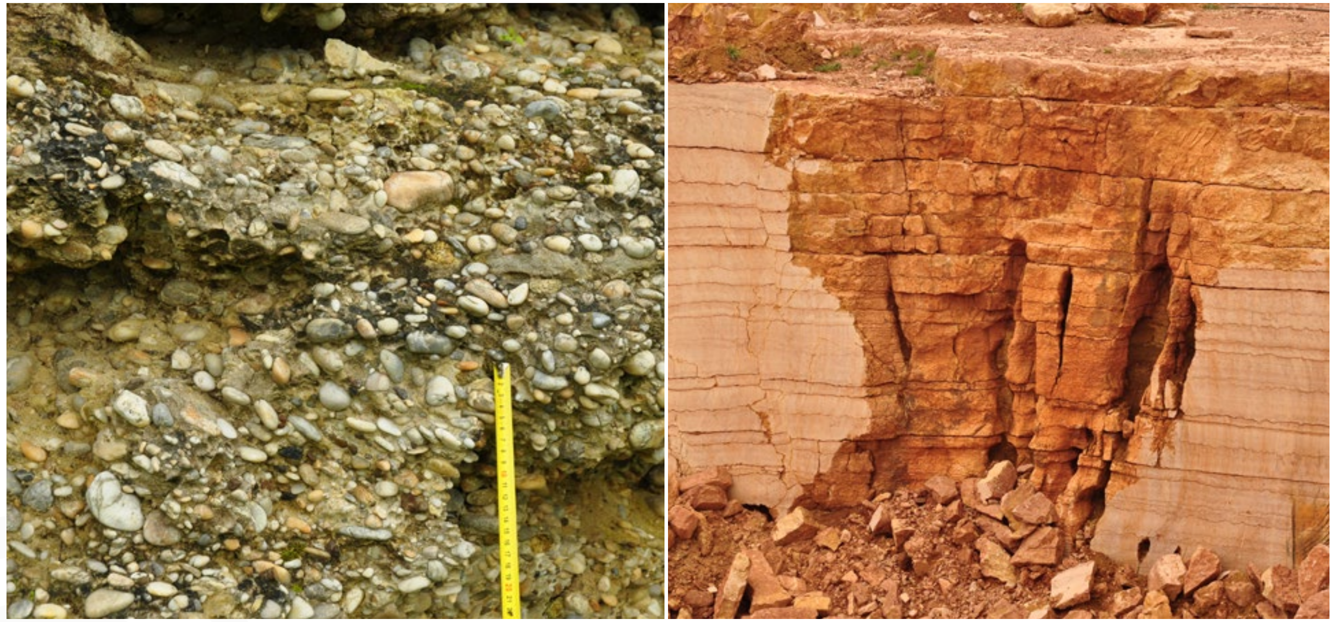
SUCCESSFUL REINJECTION IN FRACTURED AQUIFERS

Fractured aquifers are connected to brittle rocks that are mostly carbonate, crystalline and volcanic formations. Here, various processes such as weathering, karstification and tectonism enhance the secondary porosity of the rock frame. This is increased to such a level that these reservoirs can store thermal water in quantities sufficient for economic exploitation.

The pore space in fractured aquifers – especially in carbonate rocks resulting from karstification – may be so large that they are not sensitive to clogging, unlike porous aquifers. Clogging is a process in which small particles – such as silt, clay or scales – move within the pores due to water flow. They then pile together and significantly reduce the local permeability of an area. When the production section is properly completed so that the unconsolidated cap rocks are isolated, the injected water is filtered. Its chemical properties can then be monitored and treated in a proper way, thus reducing the likelihood of clogging near the well-bore.

Fractured aquifers are more sensitive to problems on a reservoir scale and this probably stems from the unfavourable hydraulic connection between the wells. If the hydraulic connection between the production and reinjection wells is inadequate, this might result in a rapid cooling of the produced fluid (referred to as "thermal breakthrough"). This decreases the amount of produced geothermal

Production well of a doublet in a carbonate reservoir in Bad Blumau, Austria, with a degassing unit



Left: Example of a clastic rock with intergranular porosity;
Right: Example of a carbonate rock with fissured porosity

energy. On the other hand, the lack of a hydraulic connection between the wells might cause a decrease in the reservoir pressure, and at the same time a pressure increase at the reinjection well. Both situations would result in higher operational costs and non-effective reservoir management.

The evaluation of the location of a well by hydrogeological modelling, and its constant verification with *in situ* interference and tracer tests in the production and reinjection wells should confirm the optimum hydraulic connection. In this way the characteristics of such a connection can be evaluated, and the timing of the thermal breakthrough – and thus the time needed to observe excess cooling – can also be defined. It is usually planned that the cooling takes place over a period of not less than 25 years, which is the average duration of amortisation of a geothermal project.

During the operation of any geothermal system, it is recommended that, at both wells, permanent and continuous monitoring takes place with respect to: (a) reservoir and wellhead pressure, (b) water temperature at the wellhead and in the reservoir, (c) water and gas geochemistry, (d) gas volume, and (e) the production and injection rates. Regular evaluation of these measurements should enable the recognition of any unusual behaviour of the resource in due time, thus allowing for the proper design of mitigation measures. Such regular operational control is especially needed if an adequate verification of the hydraulic connection within a doublet was not made prior to start of operation – that is, at the completion phase of the start-up preparation.

SUCCESSFUL REINJECTION IN POROUS AQUIFERS

Porous geothermal aquifers are very common in the Pannonian basin, where they are usually composed of an alternation of sandy/loose sandstone, and silty and clayey layers of variable thickness.

The specific location of a well also plays a key role in porous aquifers, since it has a major influence on the productivity and lifetime of a well. The depth of the reinjection well and its distance from the production zone will affect the aquifer pressure and timing of the possible thermal breakthrough.

The optimal location of a reinjection well is a place where the pressure supply and injected water quantity are as great as possible, the probability of thermal breakthrough is minimal, and the investment costs are as low as possible. In order to achieve these conditions, the fulfilment of several physical parameters are advised: effective porosity should be more than 20%, permeability more than 500 mD, and filtered thickness should be above 20 m.

Reinjection in porous reservoirs has many challenges. The most common one refers to the damage caused to the formation due to drilling and well activities (and even the injection process itself) which result in a deterioration of the permeability of the rocks. Clogging is mainly caused by the migration of fine particles among larger grains in the reservoir, near the well, or in the screens. Moreover, reduction of permeability may also be a result of: (a) swelling of clays, silica or carbonate scaling in the piping, well or reservoir, (b) biofilm growth, and/or (c) corrosion particles originating from the surface pipelines.

Core of a porous Upper Pannonian siliciclastic reservoir in Slovenia, from a depth of 1.4 km

Sand filters next to the reinjection well in Lendava, Slovenia

Successful prevention of such damage requires comprehensive knowledge about the processes involved. The primary aim here is to avoid sudden starts and stops of the flow. Therefore, it is advised that an accumulation tank should be built in the vicinity of the reinjection well, so as to provide an injection flow rate which is as constant as possible.

In any case, completion of the wells by under-reaming and gravel pack is essential, as is the provision of an overground micro-filtering system. The latter removes the suspended solids from the water prior to injection in the well. It is also advised that all wells are shut-down at least once a year so that their static water level can be measured and the surface piping system can be cleaned. If the pressure in the exploitation system starts increasing, the following interventions are necessary:

- filter cleaning with a compressor, hourly water sampling and visual inspections
- sterilization of the piping system
- backwashing of the reinjection well with hourly water sampling
- bottom-hole cleaning of the well, incorporating packer tests
- layer cleaning involving acid treatment.

Continuous monitoring is essential during the operation of the wells. This includes measurements of: (a) the reservoir and injection pressure, (b) water temperature, (c) the quantities of produced and reinjected water, and (d) the chemical characteristics of the wells. The aim of the monitoring is to prevent the irreversible pollution in the well area by searching for changes in the geothermal system at an early stage, and also to avoid a thermal breakthrough. Measured data should be regularly compared to modelling results.

THE CROATIAN EXPERIENCE

CASE STUDY: REINJECTION IN A DOLOMITE AQUIFER – MLADOST SPORT CENTRE, ZAGREB

At the Zagreb geothermal field, geothermal utilization for heating purposes of the Mladost Sport Centre (SRC Mladost) began in the 1980's. By 1986, 16 wells had been drilled. The producing aquifer is the massive Triassic dolomite with its overlying limestones of Miocene age; these rocks have a hydraulic connection.

Nowadays, the SRC Mladost technological system consists of three wells: Mla-1 (monitoring well), Mla-2 (reinjection well; open hole interval from -808 m a.s.l. up to -830 m a.s.l.) and Mla-3 (production well; open hole interval from -841 m a.s.l. up to -992 m a.s.l.). Well Mla-2 is currently functioning as a reinjection well, but it can also be used as production well, if needed. All three wells end in the Miocene limestone and do

Sports park Mladost

Wellhead of the reinjection well Mla-2 in Zagreb

not reach the underlying Triassic dolomite, as this is sufficient for them to successfully tap the stored thermal water resources.

The reasons for the establishment of a closed loop technological process with a doublet were: a maintaining the reservoir pressure / yield, and b disposal of energy-depleted water (with temperature of 50 °C).

The system has been in operation since 1987 (the year of the Universiade games) and there have been no operational problems. It satisfies all the energy requirements of the Sports Park Mladost, including the heating of swimming pool water and the complex building in the winter period. Moreover, premises of the Faculty of Kinesiology of the University of Zagreb have been heated by this resource since March 2019.

The thermal water outflows from Mla-3 have temperatures ranging between 78 and 80 °C, without any submersible pump. The water is transmitted to heat exchangers because of its high CO_2 content. Since the system is closed, all the CO_2 stays in the water and is injected back into the aquifer. A secondary circuit (with tap water) has been established for energy transmission to the end users. The heat station is located under the large winter swimming pool, and so all heat losses are also indirectly used. After this, the waste thermal water, with a temperature of 50 °C, is injected into the same aquifer via the Mla-2 reinjection well (which is slightly shallower than the Mla-3 production well). The average pumping rate is 9 l/s.

THE HUNGARIAN EXPERIENCE

The exploration of thermal water has been going on for nearly 100 years in Hungary, both from porous aquifers and fissured bedrocks. Therefore, many examples can be presented, but the one selected here is the heating system of the University of Szeged.

CASE STUDY: REINJECTION IN A POROUS AQUIFER – THE UNIVERSITY OF SZEGED

The University of Szeged decided to use geothermal energy for their heating systems, and two geothermal systems were built in 2014. In the respective cases of both projects, thermal water with temperatures ranging between 92-95 °C is produced from 2000 m-deep wells at two locations

The iron filters for reinjection

Pump station for reinjection wells

(namely, the downtown of Szeged and in Új-Szeged); the water is reinjected through 2-2 reinjection wells at each location.

The producing porous aquifer consists of Upper Pannonian, poorly-cemented sandstone. This sandstone is of low-to medium solidity, and may reach a thickness of 2000 m. Therefore, several aspects had to be considered during the construction of the reinjection wells in order to achieve their successful commissioning:

- The well structure had to comply with the optimum energetical and hydrodynamic requirements
- The deep filtering and the filter frame stabilization technologies were very important
- The pollution of the water-bearing and water-absorbing layers had to be avoided during the drilling of the wells.

The Hungarian experience confirmed that accurate treatment carried out alongside surface and deep filtration of the injected water represent the main pillars of the sustainability of such reinjection projects. In these projects the final surface filtration technology was adjusted in line with the hydrogeochemical analyses of the water and experience gained from the test-runs.

The filtration capacity depends on the pore size of the sandstone. The blocking of pore throats – which have a diameter of 10-15 microns – is avoided by filtering out floating solids larger than 10 microns. The filtration technologies operating in the Szeged system are as follows:

SZETÁV North 1A Boiler room

- 80 μm mechanical (strainer) metal filters which catch larger impurities and waste materials
- 10 μm mechanical (strainer) metal filters which catch micron-sized particles

This technology enables counter-current washing of the filtered material, and thus allows for periodical cleaning and regeneration of the well and the system.

Based on the knowledge acquired from the best practices, the District Heating Company of Szeged (SZETÁV) has decided to build nine geothermal systems with 9 production and 18 reinjection wells. In this way the use of geothermal energy can be integrated into its heating circuits.

THE SLOVENIAN EXPERIENCE

In north-eastern Slovenia, up until now three reinjection wells have been drilled in the Upper Pannonian sandy geothermal aquifer. However, since 2009 only one has been properly tested and used for its original purpose.

CASE STUDY 1: REINJECTION IN A POROUS AQUIFER – NARAVNI PARK TERME 3000, MORAVSKE TOPLICE

Naravni Park Terme 3000 is a large health and spa resort where the cascade use of thermal water has been applied since 1964. Heat and thermal water are produced by two cascade systems; the first one provides space heating and cooling for hotels and spa facilities, sanitary water heating, and greenhouse heating for tomatoes; the second system is used for balneology and swimming facilities.

A regional and transboundary Upper Pannonian, loose sandstone geothermal aquifer is tapped at the site by two wells. A vertical production well (Mt-6/83) uses a submersible pump to discharge thermal water with temperature of about 58 °C. It has little free gases and does not cause scaling or corrosion.

The risk of reservoir depletion due to the increasing need for thermal water exploitation was identified at the site as early as the 1990s. Therefore, an inclined, almost kilometre-deep reinjection well (Mt-7/93) was drilled in 1993 to return energy-depleted thermal water from the Mt-6/83 well. This was the first ever such geothermal doublet system in Slovenia, and in the years following the injection capacity of the new well was occasionally tested. Approximately one third of the produced water was successfully injected at a rate ranging from 1.0 to 5.4 l/s, with a temperature between 40 and 54 °C. The wellhead pressure at the reinjection well did not exceed 1.8-2.7 bars, which is a very good and favourable measurement.

Wellhead of the well Mt-7 in Moravske Toplice

Later, the well was shut down and only in 2000 was it converted into a production well due to spa development and the increased need for thermal water. It has been successfully operating as a production well ever since.

CASE STUDY 2: REINJECTION IN A POROUS AQUIFER – PETROL D.D., LENDAVA

In 1994, the construction of a 1.5 km-deep production geothermal well (Le-2g/94) began in Lendava for the purpose of heating residential and commercial

Microfibre filters in the vicinity of the reinjection well in Lendava premises. The well was designed to tap the Upper Pannonian porous geothermal aquifer and use a submersible pump to discharge thermal water with a temperature up to 66 °C. No major scaling or corrosion has been observed in the system.

In 2007, a 1.2 km-deep vertical reinjection well (Le-3g/08) was drilled about 700 m away from the production well. Monitoring has shown that these wells are hydraulically connected. This is the only geothermal doublet which is at present operating in Slovenia. Since 2011, it has been providing geothermal heat for the district heating system of the town of Lendava (since 2017 it has also been servicing 65,000 m^2 of residential buildings, including snow melting on pavements). Existing heat energy production consists of primary and secondary circuits. If the available heat in the primary circuit plate heat exchanger is not sufficient, the high-temperature heat pump and gas boilers provide additional heat in the secondary circuit.

Several hotels, indoor and outdoor swimming pools are heated with geothermal energy at Terme 3000

Energy-depleted thermal water of approximately 45 °C is injected back into the aquifer (the temperature of the fluids is approximately 80–85 °C at reinjection depth). This takes place through reinjection well Le-3g/08 at a rate below 25 l/s, and at a wellhead pressure of approximately 4 bars. In order to prevent clogging, three-stage mechanical filtering of suspended solids is performed prior to injection. Sand and two microfibre filters are used for the removal of any particles with a diameter over 10 μm. If the injection pressure increases, the flow through sand filters is reversed and the 20 and 10 μm microfibre filters are replaced. Additionally, cleaning of the well is performed once or twice per year. While cleaning is in progress, the flow direction is reversed and the well is activated to produce thermal water by a 20-bars compressor (backwashing).

CASE STUDY 3: REINJECTION IN A POROUS AQUIFER – MUNICIPALITY OF MURSKA SOBOTA

Murska Sobota is a town which has a history with respect to the use of thermal water. The first two geothermal wells were drilled in the late 1980s. Sob-1/87 and Sob-2/88 are, respectively, almost 900 m-deep vertical wells. They produce thermal water of about 48 °C from the Upper Pannonian geothermal aquifer and the Middle Miocene turbiditic sandstone. Therefore, this water has higher mineralization and free CO_2 gas content in comparison to the other sites presented in this booklet. However, the only operational issues concern is the risk of blow-outs. The water was originally used for district heating and is still used for hotel and sanitary water heating, and for heating a swimming pool. However, it is not employed as much as it was in the past.

Drilling set at the production well Sob-3g in Černelavci

In 2012–2013, the Municipality came up with a plan to promote geothermal district heating of the Tourist Centre Fazanerija, and for this purpose a new geothermal doublet was drilled. The production well (Sob-3g) is 1.5 km deep and reaches basement metamorphic rocks (gneiss) at 1.1 km. The reinjection well (Sob-4g) is 1.2 km deep. Both wells tap predominantly Middle Miocene turbiditic sandstones, but the Upper Pannonian porous aquifer is also exploited. The gneiss in the basement is not productive. The thermal water reaches temperatures up to 58 °C. For recent research only the production characteristics of the wells were investigated.

The reinjection well Sob-4g was never properly tested for injectivity. The Municipality stated that there are two issues blocking the further use of the identified geothermal resources. The first involves the operating costs of reinjection, of the surface piping systems, and of the concession fee. The second issue is that the heating systems of the residential buildings are often not suitable for thermal water application, as they were designed as high-temperature systems; thus the lower- temperature geothermal fluid is not capable of supplying such systems. Nowadays, the Municipality uses gas, biomass and coal, and also shallow open loop (water-water) geothermal heat pumps to heat the city.

OUTLOOK

The most promising geothermal reservoir in the DARLINGe project area consists of an extensive sequence of Upper Pannonian loose sandstone layers. They form a transboundary, hydraulically continuous porous aquifer, represented by the so-called “basin-fill” reservoir.

In order to support energy-efficient geothermal development in the region, the number of users and the total quantity of produced geothermal energy have to be increased. This can be achieved if pilot or demonstration projects involving new reinjection wells are applied at the current production sites. However, the establishment of such new geothermal doublets will require financial support.

Transparent and intensive dissemination activities will be needed at all stages of such project development (i.e. preparation, design characteristics, cost evaluation). These are crucial factors for the replicability the geothermal doublets.

DARLINGe project is promoting the sustainable utilization of the existing, however still largely untapped deep geothermal resources in the heating sector at the southern part of the Pannonian basin.

For further information, please visit our website: http://www.interreg-danube.eu/approved-projects/darlinge or contact the project coordinator – nador.annamaria@mbfsz.gov.hu

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