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THE APPLICABILITY OF COMBINED HEAT, POWER AND METAL EXTRACTION AT HUNGARIAN GEOTHERMAL CONCESSION AREAS

TDK Study

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Table of content

1.	Introduction, objectives	1
2.	Literature review	2
2.1.	Introduction to geothermal energy	2
2.2.	Development of a geothermal project	6
2.3.	Geothermal reservoir types.....	7
2.3.1.	Conventional approach.....	7
2.3.2.	Non-conventional approach.....	8
2.4.	Accessibility	10
2.5.	Utilization of geothermal energy.....	12
2.6.	Environmental assessment for geothermal exploitation.....	18
2.6.1.	Environmental challenges associated with geothermal exploitation..	19
2.6.2.	Environmental concerns of geothermal energy compared with fossil fuel based energy production.....	20
2.7.	Hydrometallurgical technologies combined with geothermal energy utilization	21
2.7.1.	Hydrometallurgical technologies.....	22
2.7.2.	Ongoing projects on the co-production of combined heat, power and metal extraction	28
2.7.3.	Challenge associated with high mineral content brine	32
3.	Screening the geothermal concession areas proposed by MBFH	33
3.1.	Research methodology	33
3.2.	Rating standpoints	36
3.2.1.	Geological settings	36
3.2.2.	Geothermal aspects.....	37
3.2.3.	Geochemical composition	39
3.3.	Short summary of the examined areas.....	39
3.3.1.	Gödöllő.....	39

3.3.2. Ráckeve	41
3.3.3. Gádoros.....	44
3.3.4. Ferencszállás.....	46
3.3.5. Kecskemét	48
3.3.6. Battonya.....	51
4. Selection of the two most advantageous regions for further investigation ..	54
5. Conclusion.....	58
6. Summary.....	59
7. Összefoglalás	60
8. References	61

1. Introduction, objectives

Hungary has a great geothermal potential due to the thin lithosphere below the Pannonian Basin. However, the resources are being exploited only with a capacity factor 0.47 % (J. Lund, Freeston, & Boyd, 2010). Increasing financial feasibility of geothermal projects would be the key factor for blooming geothermal industry. In order to achieve that and making an additional value, extracting precious compounds from the brine, like K, Li, Mg, Zn, offers a completely new solution, that is worth further research. Some geothermal fluids are rich in mineral content, some are mineral free. Mineral recovery from geothermal brine is a viable technology that offers several benefits. The two main benefits are improving the function of the geothermal power plant (e.g. reducing scaling) and increasing financial feasibility by extracting minerals. Many geothermal brines contain precious chemical compounds such as zinc, silica, lithium, manganese, boron, lead, silver, antimony and strontium (A. Kagel, 2008).

All research starts with defining a set of questions, that researcher is aiming to answer during his/her work. Later on, the researcher sharpens the focus on one or two main questions that the whole research is built around. My main questions are the following:

Does Hungary have a potential for metal extraction from geothermal brines? If yes, which Hungarian concession areas are the most beneficial, regarding the applicability of combined heat, power and metal extraction (CHPME) technology?

Before one can answer these questions, there are a number of follow-up questions to verify. Since CHPME is novel, innovative, cutting-edge technology, I decided to start my research at the very beginning. The first set of questions I am going to answer is related to the geothermal exploitation and hydrometallurgical technologies. *What are the basics of geothermal energy*, including the origin of Earth's heat and the frequently used terms? What are the geothermal reservoir types? How can get access to it? How is the development of a geothermal project? What are the utilization possibilities of geothermal energy and how does Hungary utilize them? What are the environmental concerns of geothermal exploitation? What kind of mineral extraction technologies are available? How many, and what sort of CHPME projects exist today? What are the challenges associated with the high mineral content brine?

Once the scientific and technological background of CHPME is explained, I am going to apply a screening process on Hungarian geothermal areas. In order to identify the advantageous areas, three main rating standpoints are considered: *geological settings*, to clear the geological environment, *geothermal aspects*, to estimate the geothermal potential and the *geochemical composition* to determine the mineral extraction potential. The geothermal concession areas I took into consideration are Gödöllő, Ráckeve, Gádoros, Ferencszállás, Kecskemét and Battonya.

The aim of the study is to answer the previous questions and point out the benefiting Hungarian geothermal concession areas, regarding to CHPME.

2. Literature review

2.1. Introduction to geothermal energy

CHPME technology based on geothermal fluid production, therefore the literature review starts with the introduction the geothermal energy. In order to have an overview on the topic, I am going to present the basic framework behind geothermal exploitation, including the structure of the Earth, origin of the heat and the frequently used basic terms.

Planetary accretion reached a peak about 4.6 billion years ago, resulting a dynamic, highly complex and ever changing system, called Planet Earth. Bigger and bigger collisions kinetic energy converted into heat, therefore the planet started to melt, which resulted the gravitational separation of the different density compounds (Hartai, 2014). Based on mostly geophysical seismic data, earth scientist built up a model, about the Earth's current structure (Fig 1.). The model includes the temperature distribution as a function of depth. Not only the early collisions, but also radioactive decay is responsible for the heat of the Earth. Most of the modern Earth heat models include the heat generated by the decay of the radioactive isotopes like U^{238} , U^{235} , Th^{232} and K^{40} (Lubinova, 1968). The decay of the radioactive elements located in the Earth crust causes the 45-80 % of the released heat to the space. With an average temperature of 15°C at the surface, the total heat energy of the Earth is 12.6×10^{24} MJ, while the heat energy of the crust is 5.4×10^{21} MJ (Bott, 1982).

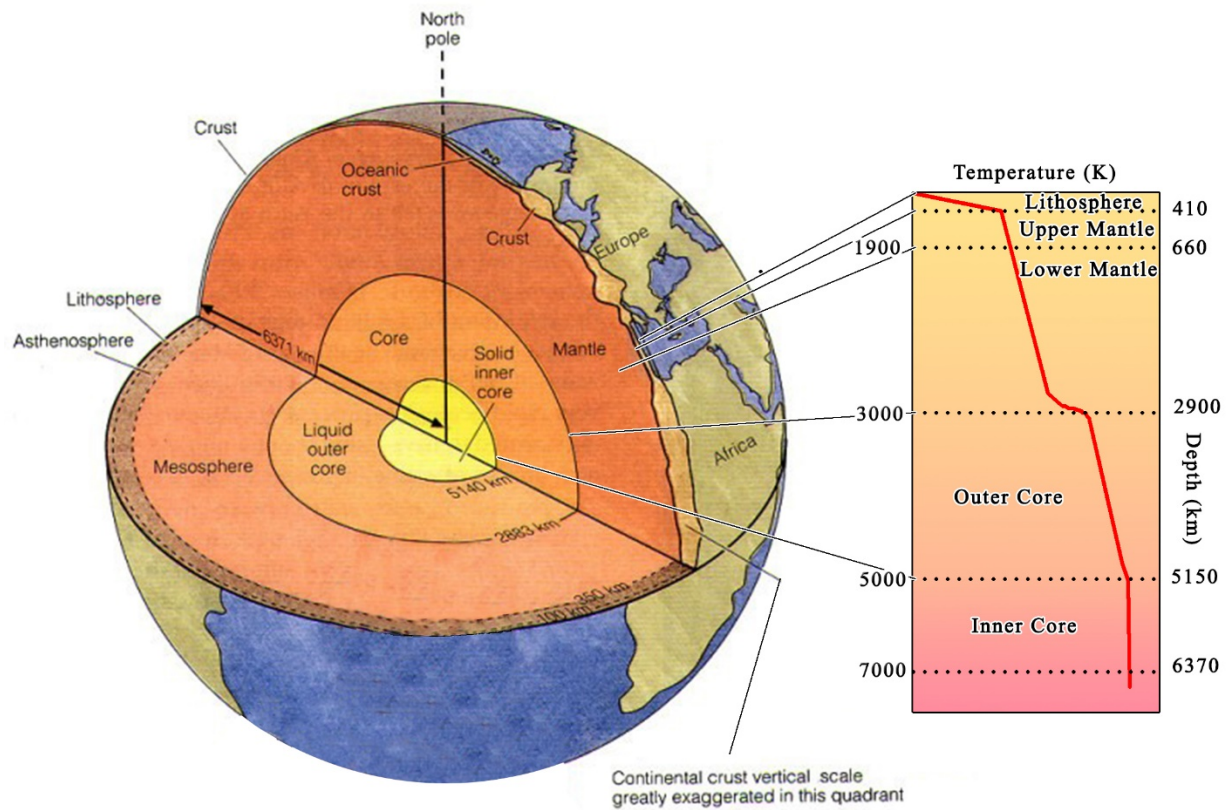


Fig. 1: The inner structure and temperature of the Earth
(after Skinner, Brian, Porter, & Koeberl, 1993, and Boehler, R. (1996))

There are some basic key words in geothermal energy that I am going to use during the study. In order to avoid misunderstanding, I am going to clarify these terms (after (Mádlné, 2006)).

Geothermal energy itself, is the part of the inner heat of Earth, which can be utilized as a source of energy (Boldizsár, 1971). According to the Hungarian Mining law (Act XLVIII. Of 1993 about mining, 49. § 11.), the exact definition for geothermal energy is *the inner heat energy of the Earth crust*.

Heat flux: the inner heat of Earth continuously flows to the surface. Heat flux describes the intensity of this heat flow. The exact number for heat flux is equal to the amount of heat energy transferred through a defined surface. The dimension of heat flux is mW/m^2 . The global average heat flux is 87 mW/m^2 , which was defined by Pollack et al in 1993.

Heat transport can have three different forms. *Conduction* occurs by the vibration of the molecules or atoms via physical contact with no remarkable movement. *Convection* is a transfer heat by the movement of the fluids driven by buoyancy forces due to density differences or by external forces. *Radiation* is a form of electromagnetic radiation, which can be observed at any non-absolute zero temperature body.

Geothermal gradient measures the rate of temperature increase as a function of depth. The measurement unit is °C/km or °C/m. The value varies between 10 and 60 °C/km, depends on the heat flux, the average mean temperature of the surface and the depth (Fig. 3).

Geothermal field is a geographic term for such areas where the heat flux is anomalously higher. Surface manifestation of geothermal activity are often present. Such geothermal fields are located in Imperial Valley in the USA, Iceland and Larderello in Italy.

Geothermal system includes three major elements. Massive *heat source* for the continuous recharge of heat. *Geothermal fluid* is the medium, which can be used to harvest the heat from the reservoir. The fluid can be water, steam or the both. . *Reservoir* is a volume of rock with a high effective porosity, functioning as a kind of heat exchanger. Geothermal fluid can penetrate through it while getting heated.

Permeability measures the resistance of the reservoir rock against water flow. The higher the value, the higher water flow can occur within the formation.

The McKelvey diagram (Fig. 4), describes what are the differences between *reserves* and *resources* are. The diagram can be applied in geothermal framework as well. McKelvey diagram gives the resource/reserve classification as a function of economic feasibility and the geological assurance. Geothermal *reserve* is a *resource* that is identified, demonstrated and economically exploitable source of geothermal fluid. If it is not economical at the current financial status, and not demonstrated but identified, it is called inferred, sub-economical reserves.

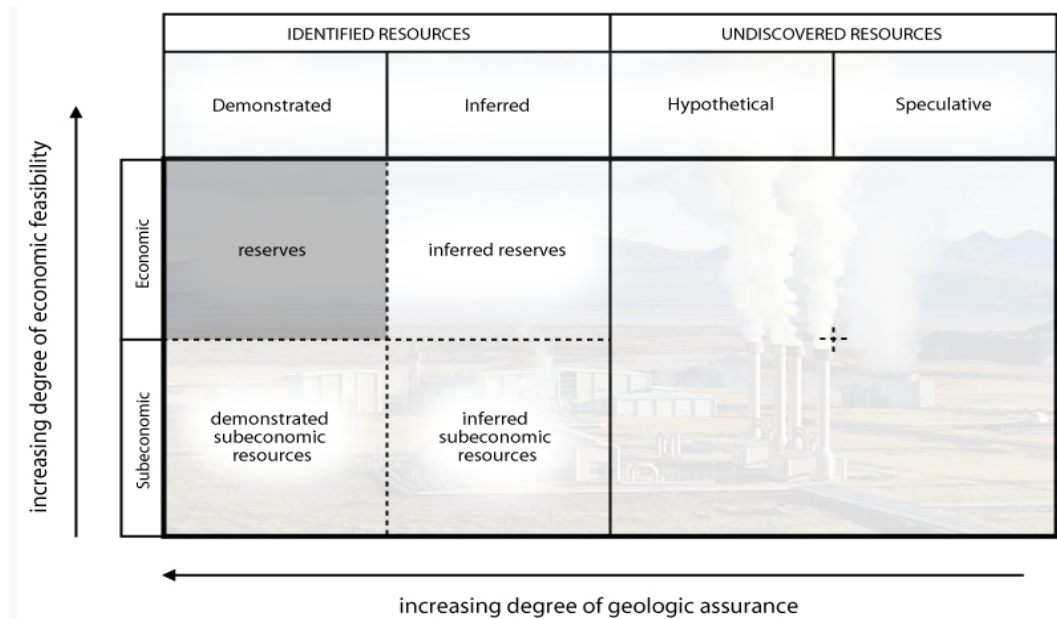


Fig. 4: The McKelvey diagram (after McKelvey, 1972)

The geothermal energy is present at any point of the world, although some places have higher, others have lower potential for geothermal exploitation. Advantageous areas are usually at active continental margins (Fig. 5)

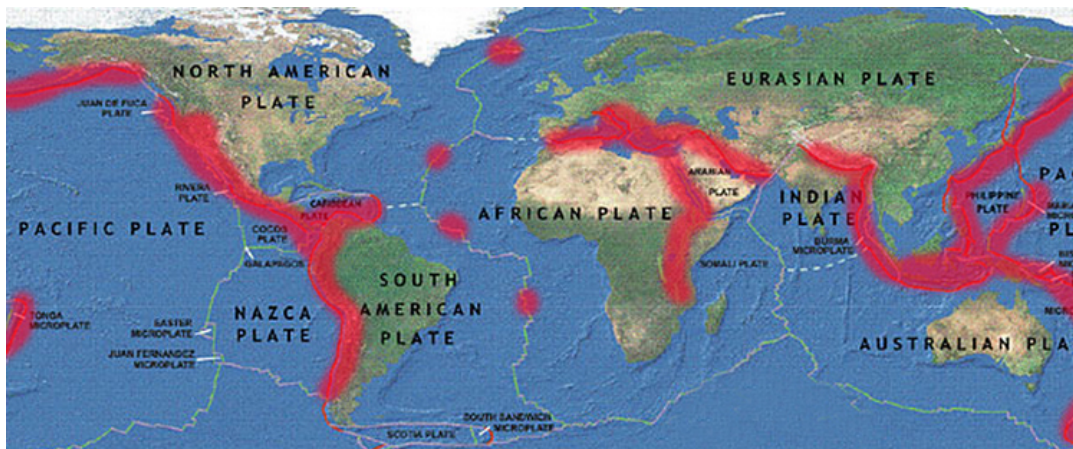


Fig. 5: Continental plates and high geothermal potential areas in red (after Mádlné Sz., 2006, picture: <http://www.platetectonics.com/>)

Volcanic activity, elevated heat flux and several surface manifestation of the geothermal potential, like hot spring, geysers, are generally present at active continent margins.

2.2. Development of a geothermal project

The development of a geothermal project is explained by a Hungarian example. The Hungarian Office for Mining and Geology (Magyar Bányászati és Földtani Hivatal, MBFH) proposes areas for geothermal exploitation. Companies can approach these areas through a concession process, according to the Hungarian law (Act XLVIII. Of 1993 about mining,) MBFH provides a detailed 150-200 page-summary about the proposed area. The study prepared according to the Government decree No. 103/2011. (VI. 29.) about complex sensitivity and loadability examination of natural occurrence territories of mineral raw material and geothermic energy. Within this study all important information is provided for the companies in order to make their decision, whether paying for the right to be only one doing further development or not. The work, after completing legal provisions and archive data research, starts with field exploration. This stage is similar to the exploration stage in the HC industry and including (after Kalberkamp, Lemma, & Desisssa, 2008):

1. geological survey: rock units, surface manifestations, age of youngest volcanic activity, alteration zones;
2. hydrologic survey: meteorological data, discharge rates of springs, water table, hydraulic gradient, mean residence time;
3. geochemical survey: chemical and isotropic composition of fluids and gases, geo-thermometry;
4. geophysical survey: temperature gradient, resistivity, gravity, magnetic and seismic methods;
5. exploration wells.

After having done all the exploration stage work, the final conceptual 3D model for the geothermal reservoir is defined. Drilling operation is the one and only technique in order to access to the reservoir (Chapter 2.4). Once borehole is drilled and the well structure is developed, the exploitation of geothermal fluid (water and/or steam) takes place. Then the geothermal fluid is converted to a marketable product. Depending on the temperature it is either used for electricity production or direct heating purposes (see Chapter 2.5).

2.3. Geothermal reservoir types

2.3.1. Conventional approach

Thermal energy is exploited from the reservoir by coupled transport processes, including convection - by the geothermal fluid, through the fractures and pore space - and conduction – within the host rock itself (Tester & Anderson, 2006). After thermal energy is exploited by geothermal fluid (brine or steam), it is converted to a marketable product, which is either electricity for the power grid or heat for direct utilization. Geothermal energy utilization is going to be described in chapter 2.5.

In order to achieve a convenient geothermal energy production, in a conventional way, a coincidence of a few fortunate event is needed at the same time and place. These are (DiPippo, 2012):

- large heat source,
- permeable reservoir,
- supply of water,
- reliable recharge mechanism,
- overlying layer of impervious rock.

Highly schematic model of a hydrothermal geothermal system is shown on Fig. 6 with the depth-temperature relationship and the water pathway.

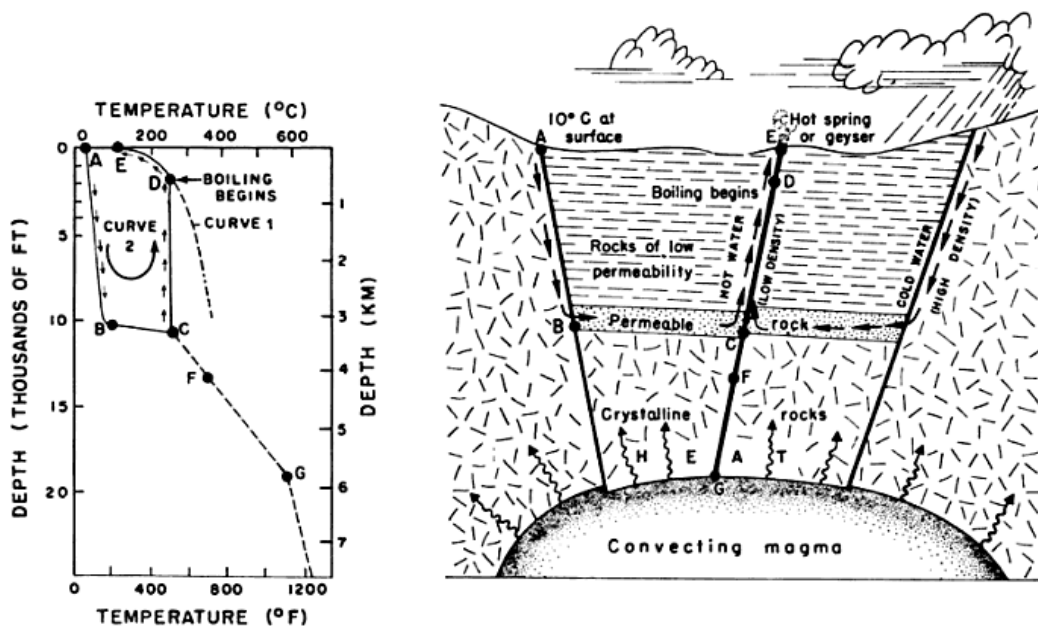


Fig. 6: Schematic model of a hydrothermal geothermal system (after (White, 1973))

Recharge mechanism is provided by the rain. Cold water penetrate trough faults and fractures from point A to B where permeable rock can be found, so water can enter the formation. As the pressure rises, the boiling point rises as well, so the water can stay in a liquid form above 100°C. Table 1 shows the relationship between pressure and boiling point at a geothermal gradient of 50 °C/km.

Table 1: Pressure-point relationship (Bobok & Tóth, 2005)

Depth [m]	Pressure [MPa]	Boiling temperature of water [°C]	Rock temperature [°C]
0	0.1	100	10.5
1000	9.6	307	60.5
2000	19.2	361	110.5

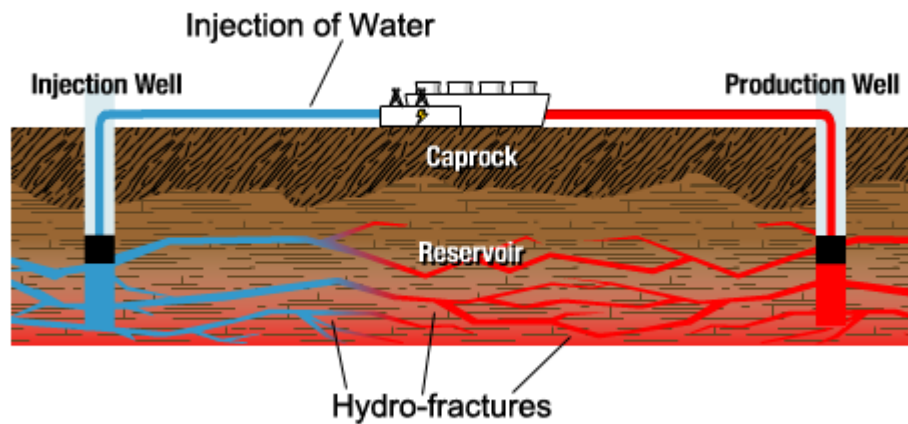
At a certain point – 22 MPa, 374 °C - water turns into a supercritical fluid. After that point water can effuse through solids like gas, and dissolve materials like liquid (Székely, 2014). Once the water is heated up by the formation, its density decreases, so the water tends to rise within the reservoir. At point C (Fig. 6), within a major fault, water can seep through the surface. As the pressure drops, at point D water starts to boil, so at the surface a geyser or hot spring can be found. The massive heat source in this system is the magma body under the permeable rock. The dominating form of heat transfer is conduction beneath, and convection within the reservoir (DiPippo, 2012).

2.3.2. Non-conventional approach

Not only hydrothermal, but other types of geothermal systems also can represent significant geothermal potential. These are Hot Dry Rock (HDR), geopressed and so called magma energy (DiPippo, 2012).

HDR systems have high temperature but either have no available fluid in the formation, or the permeability is too low to support the production. Sometimes both cases are present at the same time. The lack of water can be solved by drilling an injection well in order to meet the water demand of the production. The low reservoir porosity and permeability can be enhanced by hydraulic fracturing. Once the water recharge is granted and the porosity is increased the result is so called Enhanced (or Engineered) Geothermal System (EGS). The U.S. Department of Energy has defined EGS as *an engineered*

reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources (Tester & Anderson, 2006).



*Fig. 7: Schematic picture of a conceptual two-well EGS
(www.renewablegreenenergypower.com)*

Fig. 7 shows a simplified conceptual two well EGS in a hot dry rock. The system consist of an enhanced reservoir in a low-permeability crystalline basement, two wells - one for injection, one for production - and a power plant on the surface. Table 2 gives a status update about the target and best so far accomplished records (Bertani et al., 2008)

Table 2: EGS economic targets and achievements in 2008

Topic	Economic target	Best so far
System lifetime	20 years	5 years (Rosemanowes)
Drilling cost	12 m€ for 6 km well	5 m€ for 5 km (Soulzt)
Temperature	200 °C +	270 °C at 2.2 km (Hijiori)
Separation between wells	600 m	600 m (Soulzt)
Flow-rate	~75 l/s	26 l/s (Soulzt)
Flow impedance	0.1 MPa/l/s	0.29 MPa/l/s (Soulzt)
Water loss	10 %	0 % (Soulzt)
Thermal drawdown	10 % after 10 years	
Contact surface	10 million m ²	
Reservoir rock volume	300 million m ³	
Interests rate	~ 5 %	

In geopressured systems the pressure exceeds the hydraulic pressure. The formation fluid plays a supporting role to maintain the reservoir and partly carry the weight of the overburden. Geopressured reservoirs represent very high pressure, high temperature and relatively shallow depth, which make them attractive to geothermal exploitation (DiPippo, 2012). Such geopressured system can be found in Hungary, at Fábíansebestyén, Álmold and Nagyszénás (Árpási, Lorberer, & Pap, 2000).

2.4. Accessibility

Accessibility is very complex, challenging problem, which needs the cooperation of the best earth scientists and engineers. Drilling operation itself follows the HC industry routines with some minor differences. Geothermal drilling is more expensive than HC wells, due to three principal reasons:

1. technical challenges: harsh downhole conditions;
2. large diameter: due to the large production rate, small diameter production pipe is not efficient;
3. uniqueness: geothermal well, even in the same field, are more different than HC well in the same field (Finger & Blankenship, 2010).

Almost all HC and geothermal wells are being drilled by rotary drilling (Werner, 2008). When this method was introduced in 1882 (Ken, 2000), drilling operations become faster and more efficient. The key that makes rotary drilling widely used, is that the cutting of the borehole and the cuttings removes are being done at the same drilling phase. The simplified structure of an onshore rig is shown. During the summer of 2012, I was working for a Norwegian company (Ruden Ltd.) at an onshore drill site. Even though we were drilling shallow wells for drinking water, it was a great opportunity to learn about the drilling operation in practise. The drilling technology we used is similar to the one that is presented at Fig. 8. The three major parts are the following:

- power supply: usually diesel engine;
- hoisting system: rises, lowers and suspends the equipment;
- rotary system including the rotating drill strings, bit, rotary table and related equipment;
- circulation system: pumps the drilling mud/fluid through the borehole to remove the cuttings, control the subsurface fluid, cool and lubricate the bit, etc. (Werner, 2008)

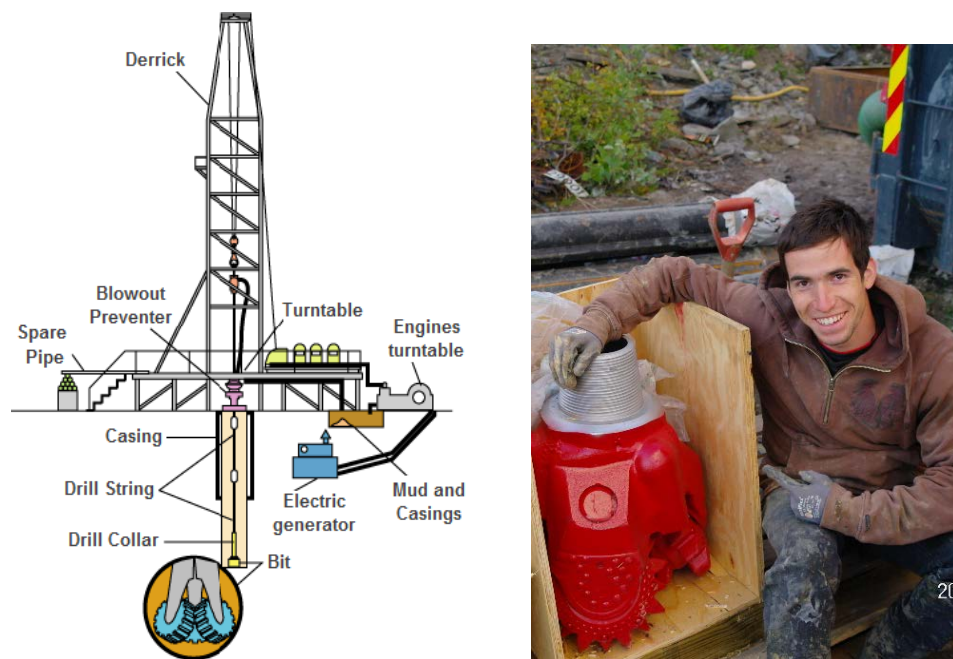


Fig. 8: The schematic structure of an shore drill rig (Werner, 2008) and a 18^{1/2} " tricone drillbit

2.5. Utilization of geothermal energy

The point of geothermal exploitation is providing marketable product, so the company can benefit from the project. According to the conventional approach the end product is either electricity power or direct heat that could be utilized in all kind way. Best-case scenario, this two application realised together, resulting an enhanced overall utilization efficiency of the plant. The two countries where it is widely practised are Iceland and Japan (DiPippo, 2012).

Baldur Lindal (1918-1997) was one of the world greatest pioneer in the field of direct utilization of geothermal energy. He developed a diagram that shows the wide spectrum of geothermal energy utilization. Ideal case is that the geothermal water is used for power generation first, then for direct heating purposes.

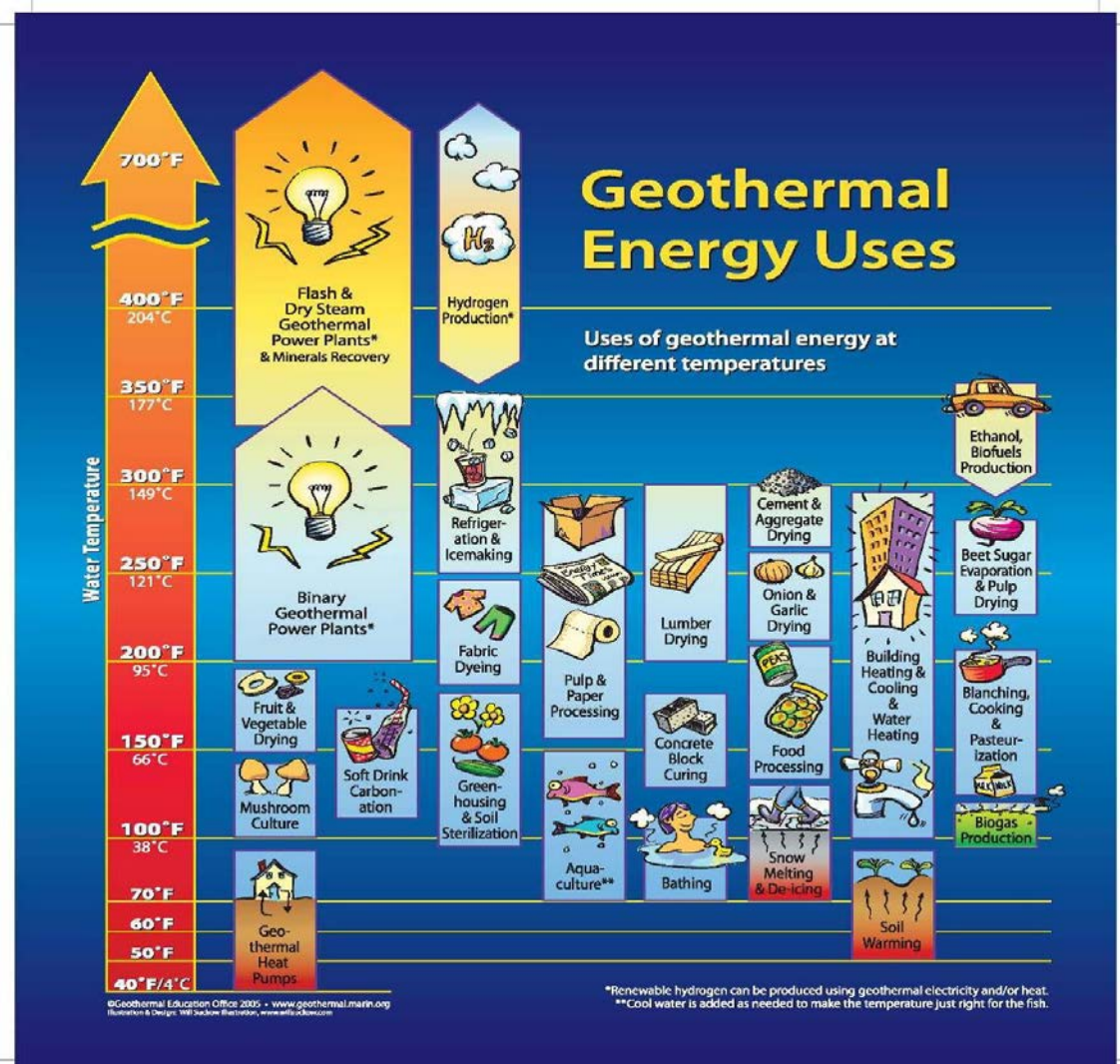


Fig. 9: The Lindal Diagram (after ,Geothermal Education Office, 2005)

The upper left corner of the diagram stands for electricity generation. In geothermal power plants the steam drives a turbine that is connected to an electricity producing generator. There are three main type of geothermal power plants.

Binary Power Plants (Fig. 10) utilize the low temperature geothermal fluid starting from 95 °C. Here the fluid passes through a heat exchanger that heats up the so-called binary fluid with a low boiling point. This secondary working fluid boils to vapour, like steam, and powers the turbine generator. The average power is 3 MW_e per unit. 39 % of the geothermal plants are using this technology

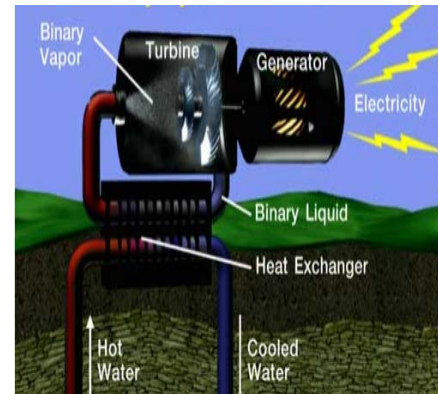


Fig. 10: Binary power plant
(www.geothermal.marin.org)

Most modern geothermal power plants are *Flashed Steam Plans* (Fig 11). The water passes through a separator so, due to the massive pressure reduction, it explosively boils to vapour that spins the turbine. These plants are using single or double flash. The latter is more costly and require more maintenance but also offer higher efficiency and power output. The average output power is 27-31 MW_e per unit (single flashed-double flashed) and 39 % of the geothermal plants are using this technology

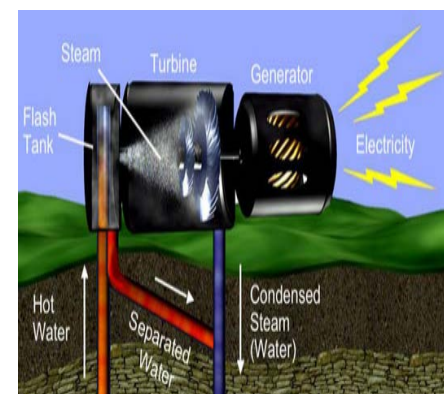


Fig. 11: Flashed steam power plant

Some geothermal fields produces mostly dry steam. In this case *Dry Steam Plant* (Fig 12) is the right choice for power generation. Here the steam shoots through a rock-catcher, to avoid damages in the installation, into the turbine (Nemzer, Carter, & Nemzer, 2000). The average output power is

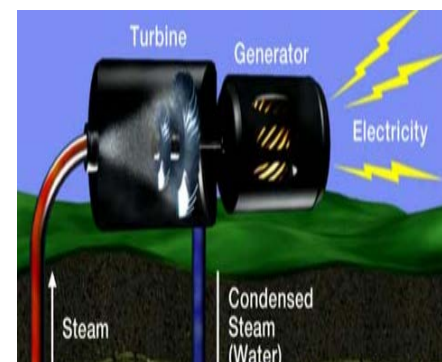


Fig. 12: Dry steam power plant

40.75 MW_e per unit and 12 % of the geothermal plants are using this technology (DiPippo, 2012)

If the produced geothermal fluid is cooler than 95 °C, or it is cooled down during the power generation, it still can be used for a number of direct heat applications. These are bathing and spas, agriculture, aquaculture, building a food industry, district heating, snow melting and de-icing. The framework behind these applications are mostly self-evident.

Geothermal heat pumps are sort of direct heat utilizations as well. The main feature of these applications that a geothermal heat pumps utilize the constant temperature of the subsoil. It can be used for either heating or cooling purposes, depending on the needs.

Hungary has always

Hot springs, as a surface manifestation of the geothermal potential, were known and utilised from ancient times. The Roman Empire, the Medieval Hungarian Kingdom and later on the Ottoman Hungary realised the advantages geological settings of the area of Budapest and built spas around the hot springs. Further exploration for thermal waters started in 1877 (J. W. Lund, Freeston, & Boyd, 2005).

Geophysical survey, using seismic and magnetotelluric methods, indicated the thinning of the lithosphere within the Carpathian Basin. Therefore the Earth's crust below Hungary is only about 25-28 km (Fig. 10), which explains the very high (40-60 °C/km) geothermal gradient.

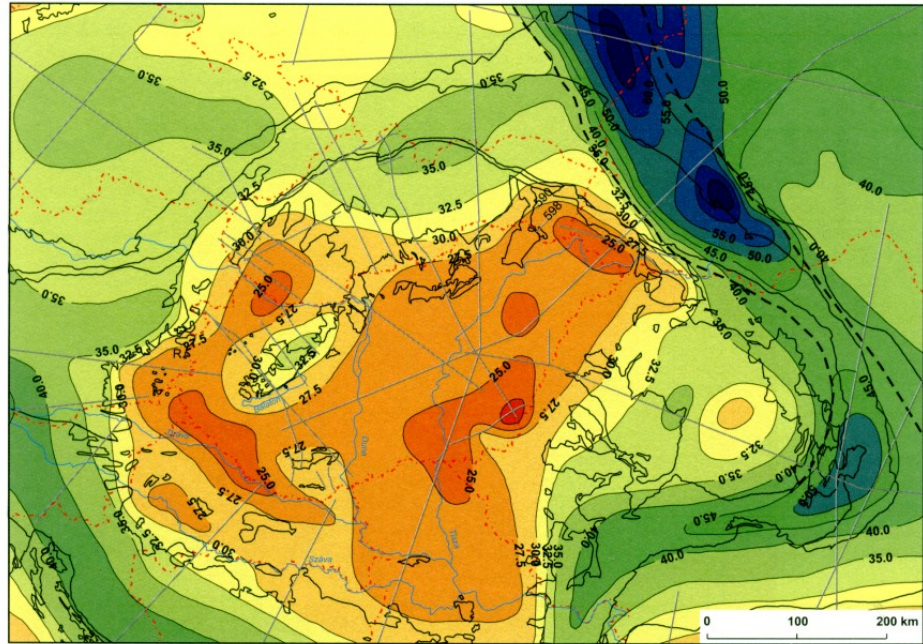


Fig. 11: Crustal Thickness beneath the Pannonian Basin and the surrounding areas (in km) (Horváth, Bada, Windhoffer, & Csontos, 2005)

The lithosphere thinning is caused by first an extensional lengthening of the crustal plate and later by a mantle diapir (dome-like protrusion). Diapir is a type of intrusion where deformable material is forced into the brittle overlying rocks. The intrusion results crustal thinning due to the mantle convection and increased heat flow. Isostatic sinking can be observed on the thinned crust where two plains were formed. These plains are filled by Quaternary, Pliocene and Upper Miocene sediments with a thickness of 1-8 km (Less, 2014). This kind of sediments could be great reservoirs for geothermal water.

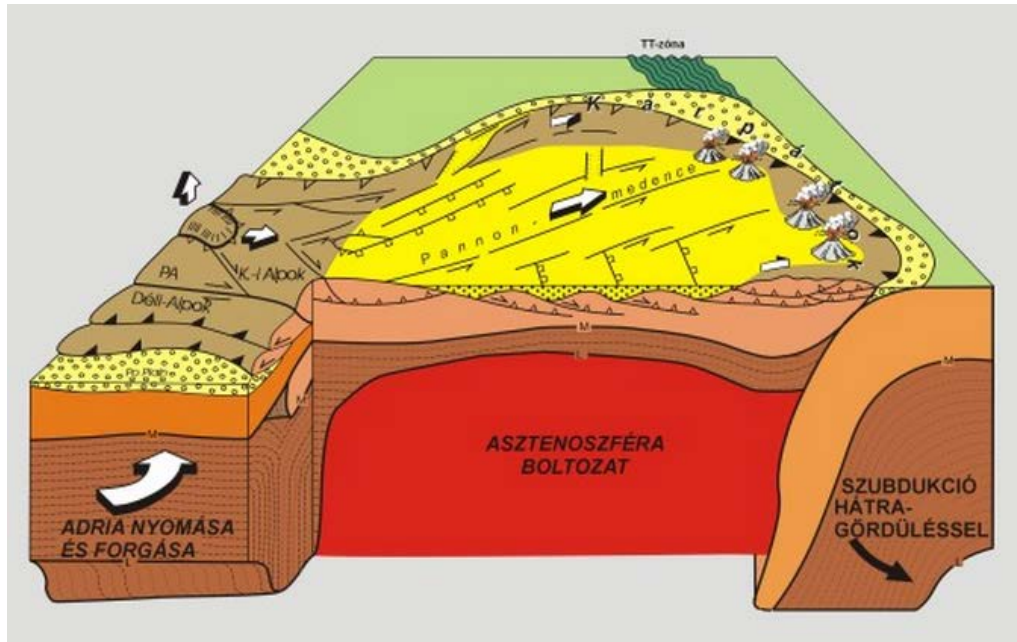


Fig. 12: The directions of tectonics development beneath the Pannonian basin (Less, 2014)

The lithosphere thinning results high heat flux and high geothermal gradient (Less, 2014, after Horváth & Cloetingh, 1996)

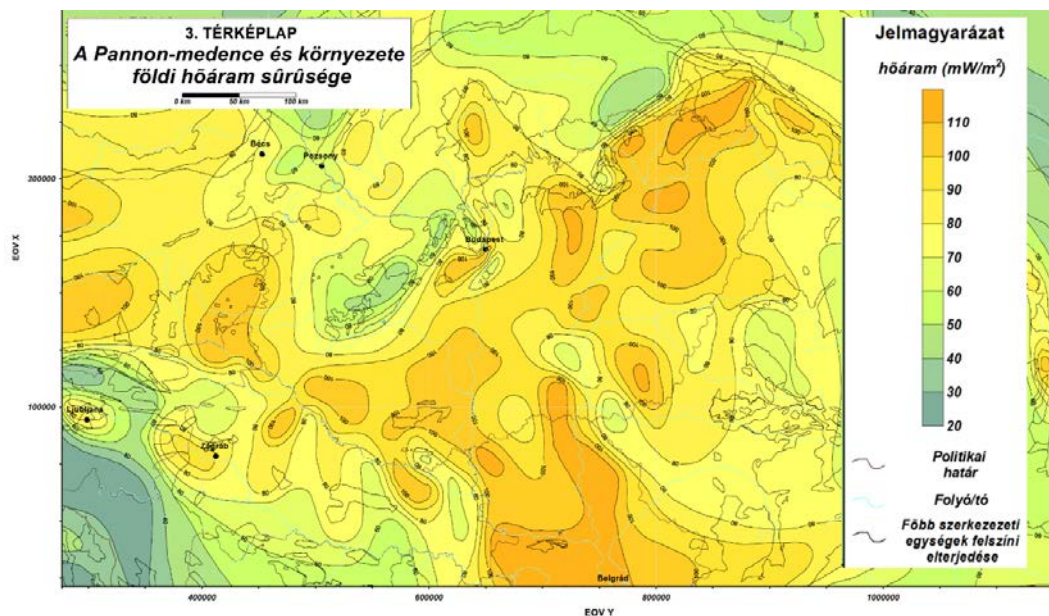


Fig. 13: Heat flux map in the Pannonian basin (Horváth et al., 2005)

Anikó N. Tóth, associate Professor at University of Miskolc, delivered the Hungarian country update in 2010 at the Geothermal World Conference, Bali. Based on the country update of Tóth, there are 289 thermal wells and 120 natural springs support

the thermal water for sports and therapeutically purposes. 193 operating wells are in the use of Agriculture, supporting 67 ha of greenhouses. Animal farming utilize thermal water in more than 52 cases to raise chickens, turkeys, calves, pigs and snails. In 2010, more than 9,000 flats are heated by direct heating projects, distributed in more than 40 townships. Oil industry use thermal water for enhanced oil recovery by injecting hot water to the reservoir at a rate of 5,400 m³. Some pipelines are also heated with geothermal fluids in heavy oil producing fields. Geothermal heat pumps had a large growth between 2005 and 2010, with more than 4,000 units installed. Table 3 summarizes the exact numbers for geothermal energy utilization (Tóth, 2010).

Table 3: Geothermal energy utilization of Hungary (Tóth, 2010)

Type of usage	Performance	Type of usage	Performance
Individual space heating	23.7 MWt; 232 TJ/yr	Industrial process heating	12 MWt; 159 TJ/yr
District heating	94.9 MWt; 930 TJ/yr	Agricultural drying	10 MWt; 123 TJ/yr
Green houses	196 MWt; 2,388 TJ/yr	Bathing and swimming	272 MWt; 5,356 TJ/yr
Fish farming	4 MWt; 44 TJ/yr	Geothermal heat pumps	40 MWt; 518 TJ/yr

Considering the geographical setting of Hungary, the most important renewable energies in the future are biofuels, geothermal and solar energy (“Nemzeti energiasztratégia 2030 /Energy Strategy of Hungary 2030/”, 2011). According to a research done by the subcommittee Renewable Energy, Hungarian Academy of Sciences, the theoretical renewable energy potential of Hungary is 2600-2700 PJ/year. The actual potential is lower due to the economic feasibility and technological challenges, but there are no available estimations for this exact value (“Nemzeti energiasztratégia 2030,” 2011). The objectives for future development of utilizing renewable energy is given by *Magyarország Megújuló Energia Hasznosítási Cselekvési Terve 2010 - 2020 (Action Plan for the Utilisation of Renewable Energy in Hungary)*, published in 2010.

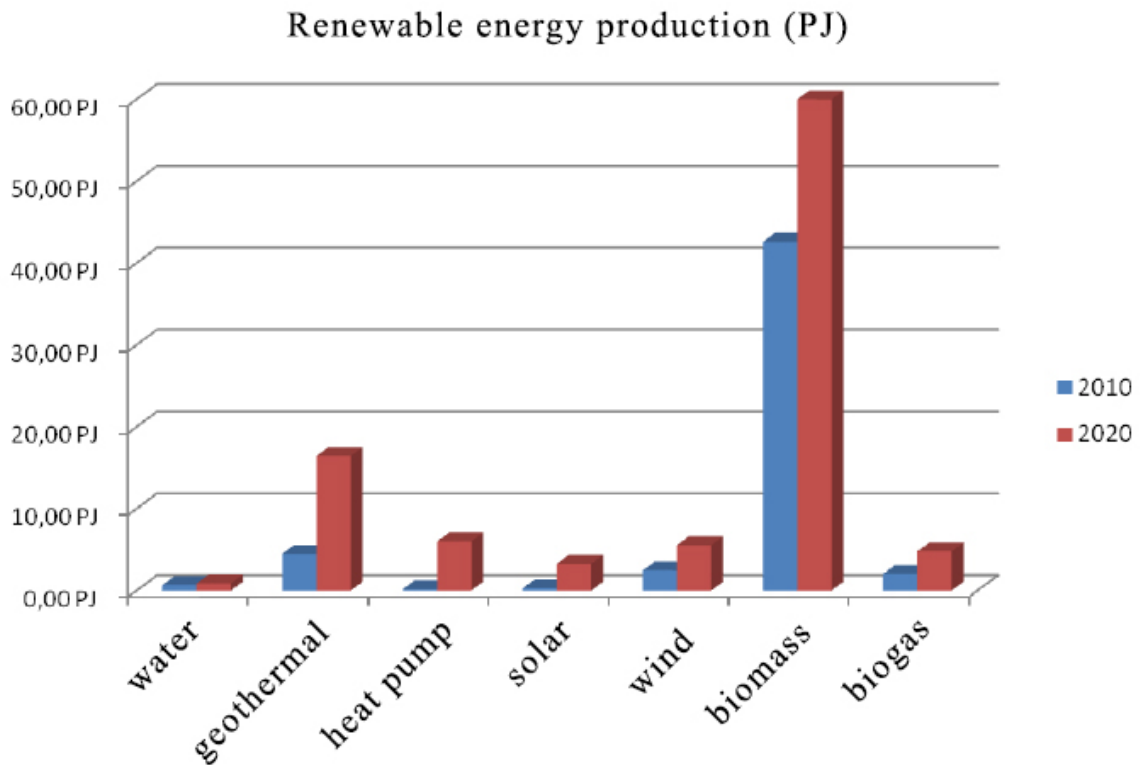


Fig. 14: Renewable energy production in PJ at 2010 and 2020 (Magyarország Megújuló Energia Hasznosítási Cselekvési Terve 2010 - 2020, 2010)

The diagram in Fig. 13 shows that biomass dominating but geothermal should have the biggest relative grow. Therefore, *working on geothermal project to increase financial feasibility is a reasonable objective in Hungary.*

2.6.Environmental assessment for geothermal exploitation

Preventing damages on the environmental is a strategic priority for the European Union. Therefore environmental assessment has to be carried out before the project development in order to realize the potential negative consequences of the project. EU lays down certain The European Commission has its own regulation and legal background to determine the development of the environmental assessment. A according to the European Commission webpage, there are two Directive concerning environmental assessment. Directive 2011/92/EU (also known as Environmental Impact Assessment – EIA Directive) applies on individual projects, such as motorway, airport, damn or factory. Directive 2001/42/EC (known as Strategic Environmental Assessment – SEA Directive) applies on public plans, programmes.

Every human activity has an impact in the environment, including geothermal exploitation. Therefore the environmental advantages, compared to fossil fuels, and the possible environmental impacts of geothermal energy needs to be reviewed.

2.6.1. Environmental challenges associated with geothermal exploitation

During the development or production stage, certain environmental impacts, associated with geothermal exploitation, are inevitable. These challenges are such as subsidence, induced seismicity, solid discharge, noise, heat pollution and landslides.

Due to the production of geothermal brine, land subsidence can occur at a various range in different geothermal fields. Larderello, the large dry-steam field in Italy, experienced negligible subsidence after a 100 year of operation, while Wairakei, New Zealand, reached 500 mm/y with a maximum depression of 15 m (DiPippo, 2012). The subsidence depends on different factors such as the rate of reinjection, geological structure and pressure regime. In case, the geothermal reservoir production is much higher than the reinjection, higher subsidence is likely to occur. If the reservoir pressure exceeds the hydrostatic pressure, the overburden is partially carried by the geothermal fluid. This case, compaction can be observed with the lowering of the pressure, due to production, which also leads to the lowering of the surface.

Induced seismicity can be observed around geothermal field under exploitation. This seismic phenomenon is caused by the change of fluid pressure which leads to the movement of the fractures within the stressed rock formation. Seismic event can happen from various reasons associated with geothermal exploitation. Some reasons are fluid injected to the reservoir, significant lowering of the initial pressure, introducing fluids to hot dry rock systems for the first time or creating reservoirs of Enhanced (or Engineered) Geothermal Systems (EGS). The likelihood and the severity of the seismic event are the function of state of stress within the formation. Despite of the negative impact of the seismicity, in EGS systems it can be used to map the fracture growth as they are being created (DiPippo, 2012). Landslides can be triggered by earthquakes, but it is highly improbable that seismic event could cause major land movement. Even though landslides occurred at geothermal fields, the cause is not always clear.

Noise and heat pollution can be considered as minor challenges. Noise is mostly generated at the development stage of the project such as road construction, excavation for the drill site and during well drilling and testing. This could disturb the nearby residents (if there are any), but with a limited duration.

Summarizing environmental challenges, one can say that environmental assessment has to be done before geothermal exploitation. Even though, most of the challenges can be fairly easily controlled with the current technology (DiPippo, 2012).

2.6.2. Environmental concerns of geothermal energy compared with fossil fuel based energy production

Comparing fossil fuel based heat and energy production, geothermal systems have much less environmental impact in terms of gaseous emission, land use, solid discharge, water usage and pollution.

Since there is a worldwide concern about CO₂ and H₂S emission, it is important to review the gaseous emission. Table 4 shows the gaseous emission from various power plants. Geothermal energy production has significantly lower or negligible amount of CO₂, SO₂ and NO_x gaseous emission compared to fossil fuel based power plants.

Table 4: Gaseous emissions from various power plants (B. A. Kagel, Bates, & Gawell, 2007)

Plant type	CO ₂ [kg/MWh]	SO ₂ [kg/MWh]	NO _x [kg/MWh]
Coal-fired steam plant	994	4.71	1.955
Oil-fired steam plant	758	5.44	1.814
Gas turbine	550	0.0998	1.343
Hydrothermal			
Flash-steam	27.2	0.1588	0
The Geysers dry-steam	40.3	0.000098	0.000458
Closed loop binary	0	0	0

2.7. Hydrometallurgical technologies combined with geothermal energy utilization

CHPME requires a new set of thinking about geothermal resources. The high mineral content geothermal brine has always been a challenge to earth scientist and engineers. Not only due to technological complications – e.g. scaling, corrosion -, but also environmental footprint of discharging high mineral content brine to nature.

Considering the topic from a different point of view, the higher dissolved solids could mean higher financial feasibility. If we think of high dissolved mineral content **not** as an environmentally and technologically disadvantages factor, **but as a source of metals and other precious elements**, the brine turns out to be a **marketable product** (Bobok & Tóth, 2005), with a **high potential of extra profit**.

Table 5. shows the amount of dissolved minerals, which goes through the 45 MW geothermal power plant of Imperial Valley, CA, each year.

Table 5: Produced dissolved minerals in tonnes/year (Bobok & Tóth, 2005)

Mineral	Production rate [t/year]	Mineral	Production rate [t/year]
CaCl ₂	300,000	Na ₂ B ₄ O ₇	13,100
KCL	160,000	Li ₂ CO ₃	11,900
Fe ₂ O ₃	39,400	Zn	10,000
BaSO ₄	30,000	MgCl ₂	9,600
SrSO ₄	27,560	Pb	2,270

For other non-metallic elements, like S, SiO₂, NaCl, CO₂, H₃BO₃, Br, J, etc., there are some examples for industrial scale production (Potapov, Gorbach, Terpugov, & Bulatov, 2008). Between 2001 and 2004 there was one industrial scale production of metal (Zn) from geothermal brine (Potapov et al., 2008). Although Simbol Mining Corp. has a testing facility, called Calipatria on Li extraction at Salton Sea.

The chemical composition of the geothermal fluid depends on:

- the temperature and pressure during the fluid- rock interaction.
- the chemical composition of the fluid;
- the composition of the rock;

NaCl, NaSO₄ and Na/CaCO₃ are some of the major geothermal fluids (Bakane, 2013). In order to know what concentration range of metal content Table 6 gives an overview on the chemical composition of geothermal fluids, mineral and seawater.

Table 6 Water chemistry for different waters (Dickson & Goyet, 1994; Maimoni, Livermore, & Field, 1982; Mercado & Hurtado, 1992; Potapov et al., 2008)

Components	Mineral waters ¹ [mg/l]	Sea water 3.5 % [mg/l]	Salton sea, USA [mg/l]	Reykjanes, Iceland [mg/l]	Monte Amiati, Italy [mg/l]	Cerro Prieto, Mexico [mg/l]
Na ⁺	65	10784	-	15300	1977	7777
Ca ²⁺	108	412	-	2560	128	404
Mg ²⁺	34	1284	68	3	<0.5	-
K ⁺	-	399	14300	2125	558	1863
Li ⁺	-	0.17	245	7.7	21.9-11	26
Cl ⁻	-	19350	-	29800	4135	14488
HCO ₃ ⁻	547	108				90
SO ₄ ⁻	-	2712	506	62	25.8	-
SiO ₂ (total)	-				700-1040	1138
TDS	900	35172	197000			36000

2.7.1. Hydrometallurgical technologies

The aim of metal/mineral extraction from the brine is to *enhance the financial feasibility* of any geothermal project.

Extracting precious components from the brine in an industrial scale is not a new idea. in the 1930s, Lardarello Company (Italy) started to drill for steam-hydrothermal deposit, aiming for industrial scale production of boric acid and borax. In 1970, the annual production was up to 15 thousand tons of chemical raw material, including 4,400 tons of boric acid, 4,000-5,000 tons of borax, 620 tons of salmiac and other compounds.

¹ The average of some Hungarian mineral water including Balfi, Szentkirályi, Natur Aqua, Theodora, Margitszigeti Kristályvíz and Tesco Aquarius.

First, the basic physicochemical methods are going to be introduced, that could be applied for metal extraction. The short description of the method, advantages and disadvantages, according to Lo, Cheng, Han, Chen, & Chang (2014), are going to be presented. Each of them aims to produce high-grade products, e.g. metals. The exact technology that the research institutes and metal extraction plans applies is usually trade secret. The companies do not publish it at all, or they publish it in such way that it cannot be copied, since they invested money on the development of the technique. However the basics, the theory behind the applied technologies are usually known. A metal extraction facility might apply one or the combination of the following technologies:

- chemical precipitation
- chemical coagulation
- ion exchange, membrane technologies
- electrochemical technologies
- adsorption using active carbon.
- biological approach

Chemical precipitation is the process that forms solids in the solution due to changes in the state of the liquid. The solid formed during the process is called precipitate. The solubility of a metals or metal complexes influenced by factors such as pH, temperature, pressure, concentration. In case the solubility exceeds a specific value, due the changes in any factor above, precipitation is likely to occur. Precipitation process can be manipulated by adding chemicals to the solution (e.g. salts), in order to decrease the solubility (Fig. 14). Once the solubility, regarding to a specified metal, decreased, the solution becomes over saturated, resulting nucleation process. The nucleons forms aggregates and these particles either settle down or filtered out using other physicochemical process. Chemical precipitation is relatively simple, inexpensive and most metals can be removed but large amount of sludge is produced during the process and the disposal of the waste cloud be a problem

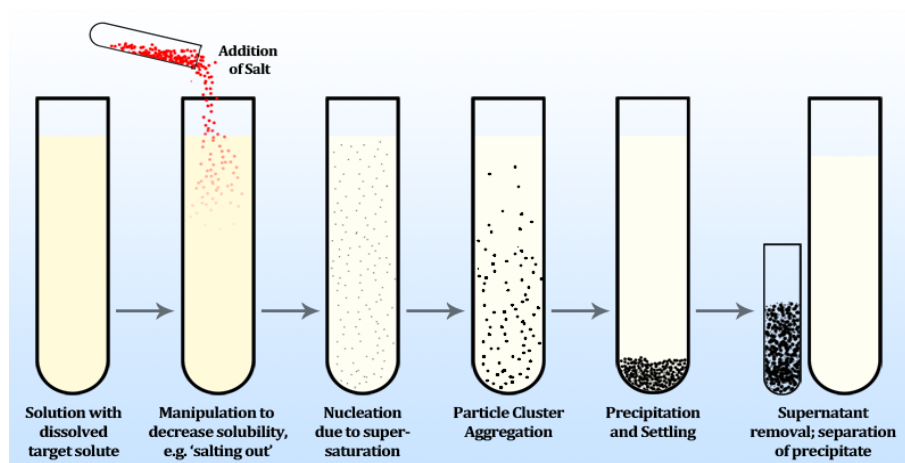


Fig. 15: Precipitation process using solubility manipulator (<http://en.citizendium.org/>)

During *chemical coagulation* particles tend to attach to each other and form blocks/flocks in the solution by induced aggregation (Fig. 15). These flocks are larger particles, therefore the metal removal from the brine is easier. Coagulants are used to enhance the coagulation, by changing the surface charge of the particle in such way that the particles “stick together”. The advantages of this technology are the faster sludge settling and the dewatering. The disadvantages are the high cost and large consumption of chemicals.

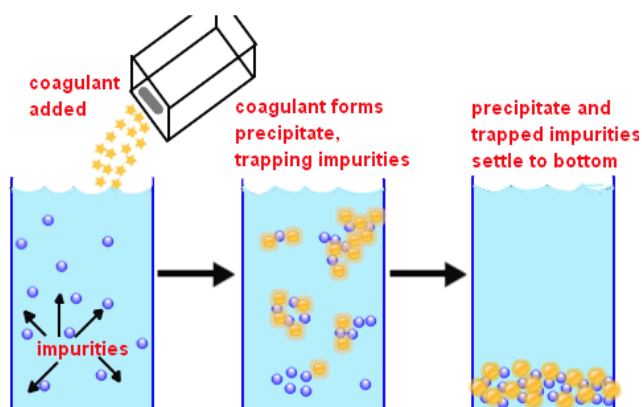


Fig. 16: The coagulation process (<http://chemistry.tutorvista.com/>)

Ion exchange is a reversible reaction between an electrolyte and a complex. The process takes place in an ion exchange resin (Fig. 16), which is a functionalized porous of gel polymer. The exchanged ion can be either anion or cation, depending on the charge. It was first used in the 1940s related to rare earth elements extraction. The technology became widely used in the industry because its simplicity, the purity of the product and

the controllable operating environment (Martinsky & Marcus, 1995). The advantages of the technology are the high recovery rate of the materials and the metal selective feature. The major disadvantage is the high cost.

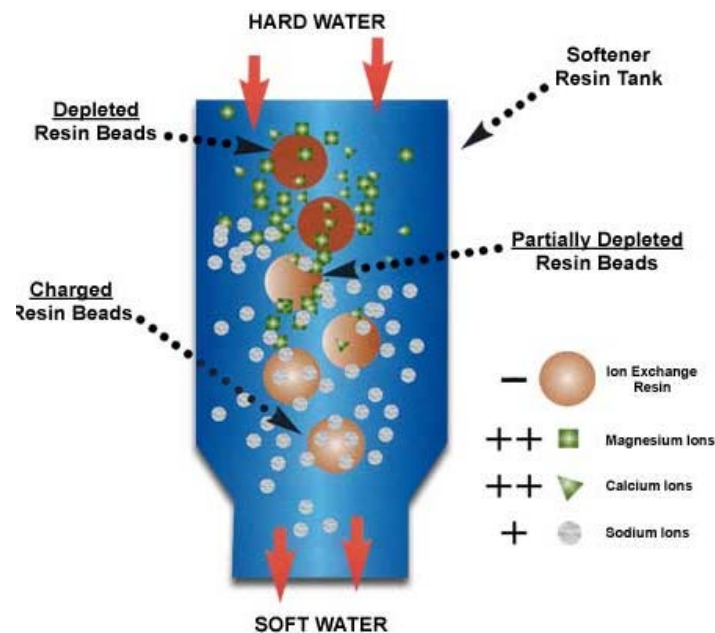


Fig. 17: Ion exchange resin used in water treatment (www.systemsaver.com)

Membrane technologies cover all kind of filtration processes that use semipermeable membrane for mechanical separation of gases or liquids. The membrane is permeable only for a given sized or smaller particle. This depending on the filtered particle size, the process is microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (Fig. 17). Pressure difference is the driving force for the fluid movement (Matsuura, 2014). The advantages of the process are the low chemical consumption, high efficiency (>95 % for a single metal) and the low solid waste production. Disadvantages are the low flow rate, high initial and running costs and the fact that the recovery rate decreases with the presence of other metals.

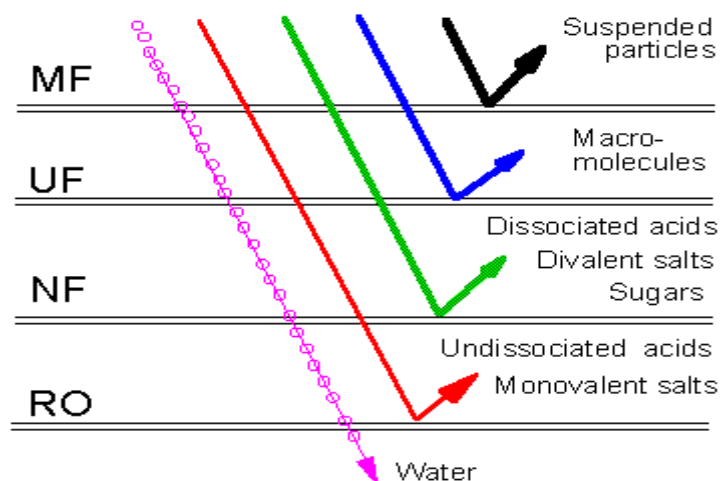


Fig. 18: The particle size distribution of microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) (www.pinterest.com)

Electrochemical technologies run chemical reactions, driven by external electrical current. The process involves electrolysis. Within this process current passes through the electrolyte which force the dissolved ions to move to the anode and cathode within the electrochemical cell (Fig. 18). In the surface of the electrode the metals can solidify. The advantages of the technology is that it is metal selective, no chemical consumption, pure metals can be obtained. The drawback of the technology is the high capital and operational costs.

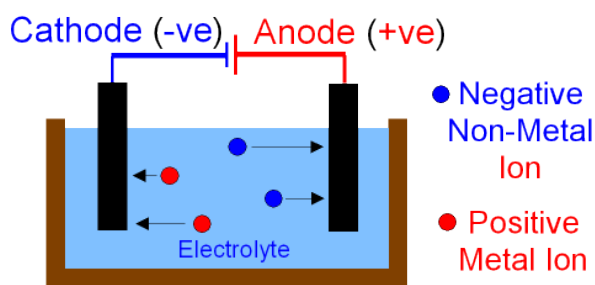


Fig. 19: Schematic electrochemical cell for metal extraction (<http://www.gcscience.com/>)

Adsorption using active carbon: Adsorption is a process wherein molecules of dissolved compound are collected and adhered to a solid surface, e.g. activated carbon. Activated/active carbon is a form of carbon that is designed to have specific pores and increased surface area. It can be used in chemical reactions or adsorption. Activated carbon (Fig. 19) has the capability to remove a large variety of compounds from the water. The adsorption capacity depends on the molecular surface attraction, the total available

surface area of the adsorbent and the concentration of the target component in the fluid. (Shepherd, 2003).

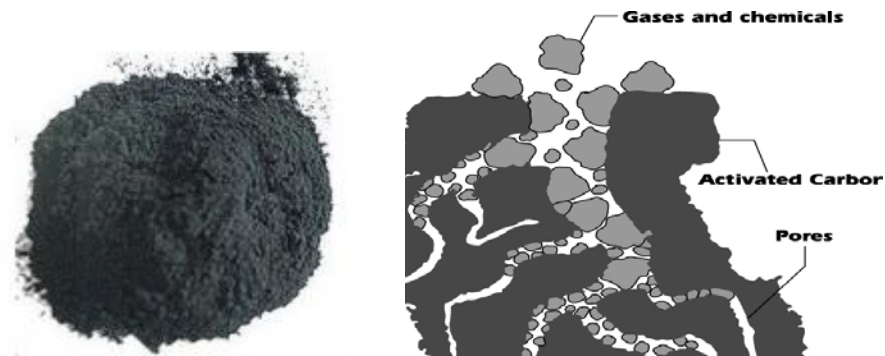


Fig. 20: Activated carbon in powder form and adsorption mechanism (www.sswm.info and www.imgarcade.com)

There are number of applications for activated carbon including wastewater management, food processing, textile, automobile, cosmetics and pharmaceutical industry. The regeneration process can be carried out via steam, thermal, chemical or biological process. Using activated carbon might be advantages since it has a high efficiency and most metals can be removed. Although the filter has to be replaced after a certain period and the cost of activated carbon is relatively high (Lo et al., 2014)

Not only physicochemical methods can be applied for high-value metal extraction. *Biological approach* offers an effective and relatively inexpensive methods. In biological methods the biosorbents either use biosorption and bioaccumulation. Biosorption is a process when the metals attach to the surface of the biocell, while during bioaccumulation the metals accumulate inside of the cell (Fig. 20).

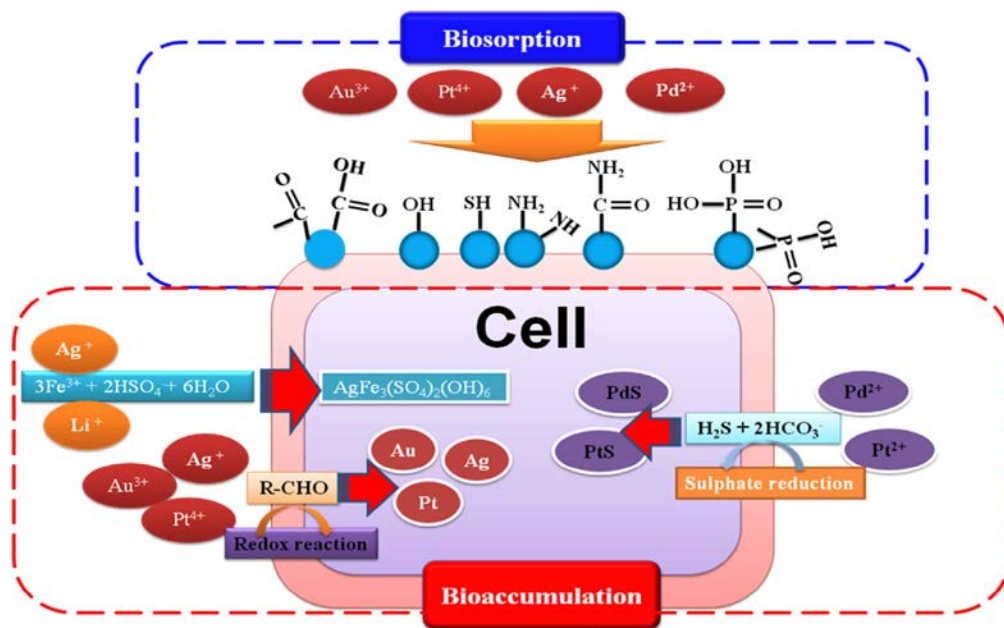


Fig. 21: Biosorption (blue) and bioaccumulation (red) (Lo et al., 2014)

Biosorption is metabolically independent, so even not viable cells can absorb metals, while bioaccumulation is usually an energy (APT) driven process, strongly connected to the viability of the cell. Biological extraction technology has the advantage of minimal sludge production, high metal uptake capacity and treatment rate. Although, the efficiency of metal extraction highly depending on the pH, temperature, concentration of the target metals and the competition of co-existing metals (Lo, Cheng, Han, Chen, & Chang 2014).

2.7.2. Ongoing projects on the co-production of combined heat, power and metal extraction

The worldwide update about the current project of combined heat, power, and mineral extraction is presented at Table 7. All of them extract some chemical component from the brine but some of them has no electricity production. Most of them extract non-metallic elements, but there are examples for metal extraction.

Table 7 Technological methods for extraction of chemical compounds from hydrothermal heat carries (Potapov et al., 2008)

Field	Extracted chemical compounds	Extraction methods	Phase of the work
Kaweraw, Wairakei, Brodlands, New Zealand	SiO ₂	Addition of CaO into separate, ultrafiltration	Pilot plant
	As	Treatment by ferric sulfate for flocculation, sorption of arsenic with preliminary pre-oxidation of natrium hypochlorite	Pilot plant
Cerro Prieto, Mexico	SiO ₂	Addition of coagulant CaO into separate	Pilot plant
	KCL – NaCl	Evaporation, crystallization, flotation	Pilot plant
	SiO ₂	Flocculants of Magnifloc, Calgon, Separan, Purifloc series	
Salton Sea, USA	Zn	Ion exchange, liquid extraction, electrolysis	Industrial production
	Fe, Mn, Pb, Ag, Cu, Sn	Precipitation of metal hydroxides after entering of CaO, precipitation of metal sulphide, cementation	Pilot plant
Mamos Lakes, USA	SiO ₂	Reverse osmosis, ultrafiltration, entering of coagulants (salts)	Pilot plant
	Cs, Rb, Li	Reverse osmosis, ultrafiltration, ion exchange	Pilot plant
Kizildere, Turkey	B	Using of selective materials – amberlite resine Amberlit IRA 743 for purification	Pilot plant
Cheleken, Turkmenistan	Br, J	Degassing, condensation, sorption	Industrial production

In favour of better understanding the previous table, here are the description for some of the processes that might not be clear:

- *ultrafiltration*: separation of particles by size, using a semipermeable membrane and hydrostatic pressure as a driving force.
- *flocculation*: when colloids come out of suspension in the form of floc or flake
- *sorption*: either physical or chemical process wherein one substance becomes attached to another.
- *coagulant CaO* results coagulation, which is a transformation from liquid to gel or solid.
- *flotation* process is widely used in water treatment for separation by the relative buoyancy of the object

- *reverse osmosis* is a process wherein the solution is forced into a semi permeable membrane where the water passes but not the solutes.

In 1999 CalEnergy Operating Corp. run eight geothermal power plant at Salton Sea. The net capacity is 288 MW. In January, 1999 CalEnergy inaugurated a \$400 million extension of their geothermal power facilities. The extension includes a new power plant unit with 49 MW capacity and a zinc recovery facility (Clutter, 1999). After a 10-month test operation the produced high grade zinc was up to 88 tons.



Fig. 22: CalEnergy Vice President of Operation, Jim Turner introduces the new mineral recovery plant, which includes an ion exchange and solvent extraction plant (right), and an electrowinning facility (left) in 1999 (Clutter, 1999)

The commercial scale operation started in 2000. The facility used the combination of some already existing technologies including ion exchange, solvent extraction and electro winning facility (Fig. 21). The wastewater with a concentration up to 600 ppm comes from eight power plants (J. W. Lund, 2003). First place the used brine with a temperature not less than 116 °C passes through an ion exchanger, similar than used in water softening. After that the separate is introduced to a liquid extraction process, where the zinc chloride is transformed into zinc sulphate. After metallurgical treatment, the end product is 30,000 tons of 99 % purity zinc (Potapov et al., 2008). Unfortunately CalEnergy closed the mineral recovery project in 2004, after 2 years of operation due to operational and economic difficulties (Bloomquist, 2006), although many believes in the future potential metal recovery at Salton Sea.

Simbol Mining Corp. is about to launch the world first industrial scale, high grade lithium extraction plant from Salton Sea hypersaline geothermal reservoir (Table 7)

Table 8: The mineral content of Salton Sea geothermal brine

Component	mg/kg	Component	mg/kg	Component	mg/kg
Na	53,000	Fe	1,500	Zn	500
K	29,000	Li	200	Cs	20
Ca	33,000	Mn	1,500	Rb	100
SiO ₂	200	Cl	180,000	TDS	31 wt %

According to Simbol's calculation, each 50 MW geothermal plant can produce 16,000 tonnes of lithium carbonate equivalent, 24,000 tonnes of electrolytic manganese dioxide and 8,000 tonnes of zinc metal from such brine. (Harrison, 2010)

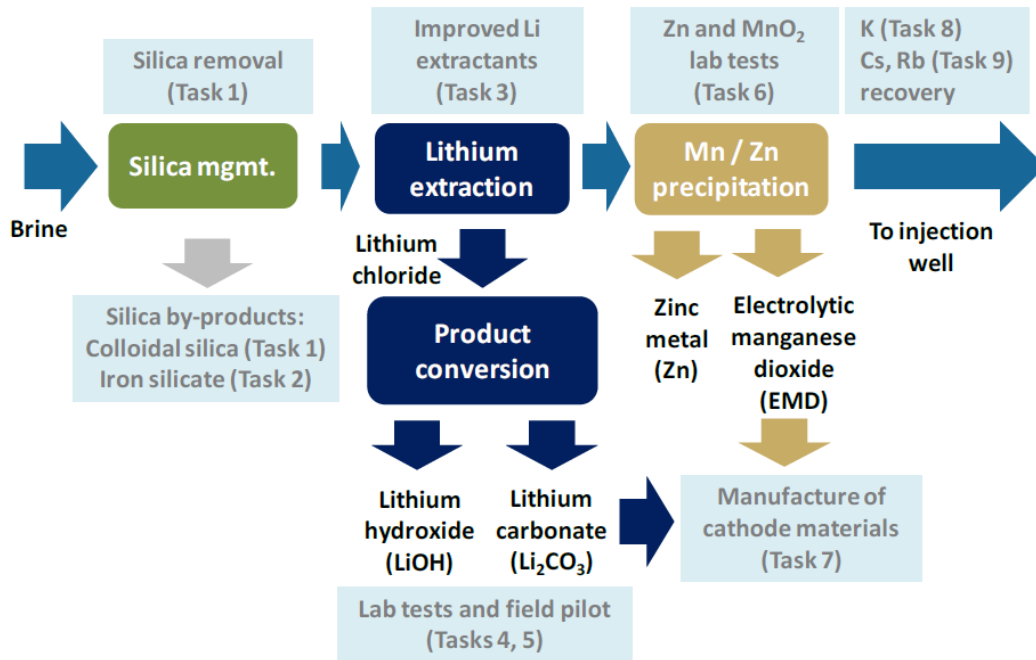


Fig. 23: Research and development plan at Symbol Minerals (Harrison, 2010)

The demonstration plant draws its brine from Featherstone 49.9 MW geothermal power plant. Simbol executives says that the test plants capacity could be scaled up from 23 l/min to 23,000 l/min, with 15,000 tons of high grade lithium per year. The exact extraction process is trade secret and the company received four patents on the process already. Although the workflow (Fig. 22) and the basic chemical processes are well known. The brine cools down at the power plant from 260 to 105 °C then it is transported via ground pipelines to Calpatría extraction plant. First step of the process is removing

silica and iron from the brine. In the next step, via a special process almost all the lithium chlorite is extracted which goes to the purification plant that results only high grade lithium. The test plant went online already and yield 100 tons of lithium. The commercial scale operation may involves manganese, zinc and potassium extraction. One of the main challenge here is not about extracting metals from the brine, but not to extract the unwanted compound, since the Salton Sea brine contains half of the periodic table. (Kaufmann, 2014)

2.7.3. Challenge associated with high mineral content brine

Scaling is one of the main problem associated with geothermal well production. (Evanoff, Yeager, & Spielman, 1995). Any kind of material that appears on the surface of the geothermal pipes is called *fouling* or *scaling*, which could be a result of changes in temperature, pressure and pH (A. Kagel, 2008).



*Fig. 24: Scaling and corrosion in a geothermal pipes
(picture: NREL, Keith Gawlik)*

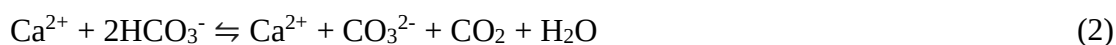
The main problem with scaling at the first stage is that it increases the friction factor of the pipe and the turbine blades. Precipitation is likely to occur where the brine reaches the boiling point, e.g. in the production pipe.

Generally there are three basic classis of scale:

- Silica and silicates
- Carbonates
- Sulfates and sulfides

Silica acid is often present in the brine from the dissolution of the formations. When silica acid, Si(OH)_4 saturates, nucleation process starts, colloidal silica forms (Eq. 1) which is absorbed at the inner surface of the pipe (Baba, Demir, Koç, & Tuğcu, 2015).

Carbonate scaling is a result of the precipitation of the carbonate content of the brine (Eq. 2). The driving forces to carbonate scaling are similar to silica scaling, but with carbonate precipitation.



Later on the mineralization can even block the pipes (Fig. 14), unless there is no treatment in order to avoid scaling. The following methods can be used:

- use of fins on the inner surface of the pipe;
- use of copper-nickel alloys. Carbon steel can be used at low cost to reduce corrosion;
- pH modification;
- flow rate should be managed in such way, that scaling is minimalized (Bakane, 2013).

Corrosion means the destruction of a metal by chemical or electrochemical action of the surrounding environment. The corrosive effects depend on the chemical composition of the geothermal fluid. Geothermal waters have a wide range of chemical composition. Acidic waters contain sulphur and halogen acids which lead to active corrosion (Fig. 14) (Elguedri, 1999).

3. Screening the geothermal concession areas proposed by MBFH

3.1. Research methodology

MBFH provides an extensive study about the suggested area, so-called complex sensitivity and loadability study about the concession area that is available on the homepage of MBFH, which makes the research faster. In these studies I was looking for relevant information for my research. Since I needed very specific data about the areas, which was not included in these studies, I continued my research in the archive data warehouse. Both MOL Plc. and MBFH supported me in this work. I spent 4 weeks as an intern at MOL

Plc. at the headquarter, centre of Budapest and at the data warehouse, Békásmegyer. During my internship I started the research with only four areas. Two of them were geothermal concession areas, Ferencszállás and Battonya. Here the relatively low depth of the granitoid base rock could result a higher concentration of dissolved minerals in the water bodies.

The other two areas are at the neighbourhood of Mecsek Mountains, at Dinnyeberki and Magyarmecske. There is a buried impact crater at Magyarmecske at a depth of 600-800 m (Bodoky, Kis, Kummer, & Don, 2006), which could result an elevated metal content in the surrounding water body. Dinnyeberki could be a potential research area, due to the local uranium deposits. Pilot extraction started in 1983 by in situ leaching, but the work has stopped in 1989, due to the shutdown of Hungarian uranium mining. Since I could not find any water analyses from those water bodies, I decided to choose other geothermal concession areas for further investigation.

Fig. 25 shows the location of the concession areas, proposed by MBFH.

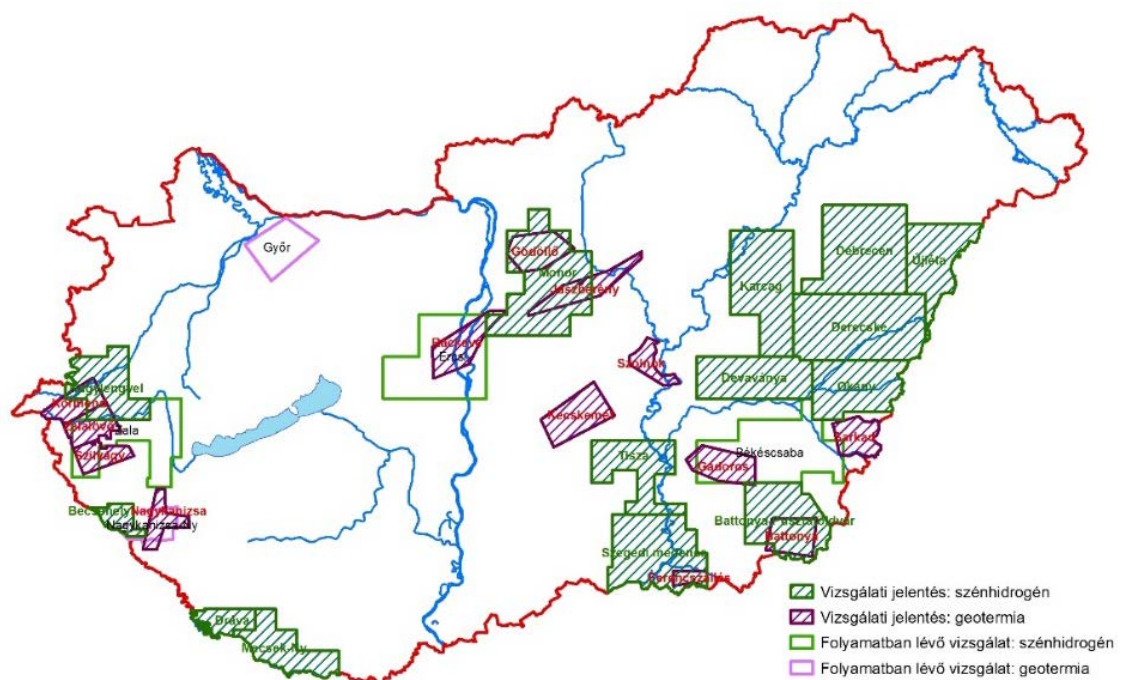


Fig. 25: The location of the concession areas: geothermal in purple, HC in green, proposed by MBFH, 2014. (www.mbfh.hu)

The concession areas, which I chose for screening, are Ferencszállás, Battonya, Ráckeve, Gödöllő, Kecskemét and Gárdoros. There are either HC or geothermal wells in each area. The list of these wells is given in the study released by MGFB, with the location, well ID, depth, etc. Most of these deep wells (>1200 m) are drilled for HC

exploitation but only some of them had actual production. Almost every well has a ~50-page logbook, or well logbook, with all the available documentation collected about the well. The logbook includes all the basic information including:

- date and place for drilling,
- applied technology and used equipment,
- archive data before drilling,
- daily reports during the drilling operation,
- basic and advanced sample description,
- formation tests,
- *water analysis*,
- maps of the region and geological structure.

During the 4-week internship and after that until now I have reviewed 213 logbooks, searching for water analysis at the first place. Water analysis includes the followings:

- date, place, institute and ID of the laboratory analysis, person who run the test,
- well ID, depth of perforation, sampling time, volume and temperature of the of sample,
- alkalinity, pH, total and temporary carbonate hardness,
- *main anion(-) and cation(+) content [mg/l]*,
- *total Dissolved Content (TDS) [mg/l]*,
- *trace element content* from quartz spectrograph analysis,
- resistivity [ohm/cm],
- palmer classification,
- institutes which received the results.

The log books are usually available in printed version and sometime in so-called microfilm as well. Using microfilms is a very old, but rather smart way of data compression. Microfilm sheets are postcard size films with 30-35 picture of the A4 size logbook. One thick logbook can be replaced with 2 sheets of microfilm. In order to review the content, one need a microfilm viewer which looks like a cathode ray tube TV but with flat screen.



*Fig. 26 Microfilm viewer, microfilm and well log books
(www.mikrofilm.hu, www.vilaglex.hu)*

I made an excel sheet to organise the collected data from the log books. The columns are:

- Village,
- Well ID,
- EOY X and Y coordinates,
- Total and perforation depth [m],
- TDS, anion and cation content [mg/l],
- Trace elements.

Incomplete log books and water analysis are common. Not all the logbooks are available for the public. Some wells are under mining lease territories, which means that the content of the logbook is trade secret. In case of Ferencszállás and Battonya, MOL Plc. has valid mining lease for HC exploitation, therefore the log books are no public. Since I was an intern at MOL Plc. I had the possibility to access those log books for my research on condition that I shall not publish the data in such way that the exact well could be located.

3.2.Rating standpoints

I consider three main rating standpoints in order to decide whether an area is advantageous for combined heat, power and metal extraction, or not. These are the followings:

3.2.1. Geological settings

Geological settings need to be reviewed in order to get a general view about the geological environment of the study areas. For the further research, I am especially

interested in the depth of the Pre-Cenozoic basement. I am going to present a geological/seismic cross section as well, just to have an overview about the geological strata at the research area.

3.2.2. Geothermal aspects

For comparison I am going to calculate the expected geothermal potential for EGS and for hydrothermal systems.

I am using an assumption the target rock for EGS is the crystalline basement, granite for example, which can be found under the top of the Pre-Cenozoic basement. Therefore this is the minimum depth for EGS. For hydrothermal systems that depth is going to be the maximum depth, since above the basement, hydrothermal geothermal systems are more likely to be found. In each concession area I am going to calculate the minimum EGS and maximum hydrothermal heat energy potential for a 1 km^3 ($1 \text{ km} \times 1 \text{ km} \times 1 \text{ km}$) reservoir, related to the surface annual average temperature. Fig. 17 shows the position of the reservoir blocks for EGS and hydrothermal systems.

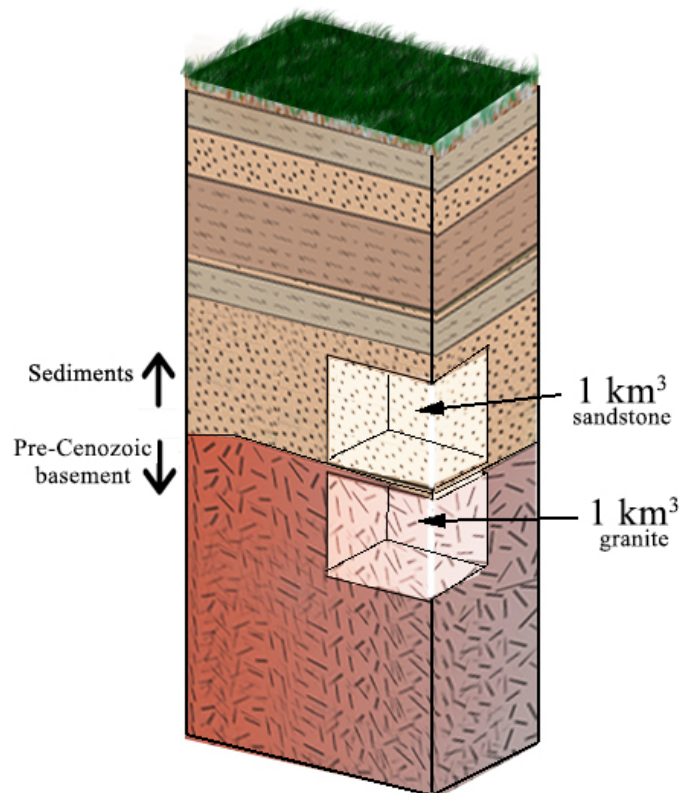


Fig. 27 The reservoir blocks for EGS and hydrothermal systems

Using hydraulic fracturing the achieved porosity could be between 1-7 % (Tester & Anderson, 2006). During my calculations I am going use 5 % for EGS and 15 % porosity for hydrothermal systems (Shaw, 1978).

Even though actual geothermal potential might be different than my calculation, but it is still valid for a comparison since I am using the same approach to all areas.

Steps for calculating the expected geothermal reserves:

1. define the depth of the Pre-Cenozoic basement
2. calculate the temperature at that level + 500 m for EGS, and – 500 m for hydrothermal system (T)

$$T = T_0 + \gamma \times Z \text{ [}^{\circ}\text{C]}$$

- T_0 : average annual temperature of the surface, $T_0 = 10.4 \text{ }^{\circ}\text{C}$ in Hungary
- γ : geothermal gradient [$^{\circ}\text{C}/\text{m}$]
- Z : depth [m]

3. define the heat energy stored in $V = 1 \text{ km}^3$ reservoir, related to $\Delta T = 1 \text{ }^{\circ}\text{C}$ temperature drop

$$q = \rho \times V \times C \times \Delta T = [\rho_R \times (1 - \phi) + \rho_W \times \phi] \times V \times C_{RM} \times 10^{-6} \text{ [PJ]}$$

- ρ_R : density of the rock [kg/m^3]
- ρ_W : density of the water [kg/m^3]
- V : volume of the rock [m^3]
- 10^{-6} refers to the unit conversation

4. calculate the heat energy that is stored by the water in $V = 1 \text{ km}^3$ of reservoir, related to ΔT temperature drop

$$q_W = \phi \times \rho_W \times V \times C_W \times \Delta T_r \times 10^{-6} \text{ [PJ]}$$

- ΔT_r : temperature difference between the surface and the reservoir

Table 9: Parameters of the sandstone, granite, water

	Density ² [kg/m ³]	Heat Capacity [J/kg×K]	Heat energy in 1 km ³ relative to dT=1K $\phi = 5 \%$ [PJ]	Heat energy in 1 km ³ relative to dT=1K $\phi = 15 \%$ [PJ]
Sandstone $\phi = 15 \%$	2,710	850	-	2.23
Granite $\phi = 5 \%$	2,650	700	2	-
Water	1,000	4,187	0.21	0.63

There are studies available about the heat flux in Hungarian (Dövényi, Horváth, Liebe, Gálfi & Erki, 1983; Dövényi, 1994; Lenkey, 1999; Rumpler et al., 1987). The presented heat flux datasets are based on their results.

3.2.3. Geochemical composition

I am going to review the geochemical composition of the water bodies at the area, in order to define the potential for metal extraction of the area. First a general geochemical description is going to be presented about the area. Then I present in the water analysis of the log books, which describes the basic anion, cation content. On the other hand trace element measurements are going to be reviewed as well. Magnesium and TDS content is mentioned in almost every water analyses, which is going to

One should not expect so high values such in e.g. Salton Sea. The hydro-geochemical settings are not like at hyper saline geothermal reservoirs, but high concentration anomalies are likely to occur, which I am looking for.

3.3.Short summary of the examined areas

3.3.1. Gödöllő

The area around Gödöllő was proposed to be a geothermal concession area in 2012. Gödöllő is located 30 km from the capital, Budapest, in a direction of NE (Fig. 18). The concession area is 405.9 km² from the depth of 2,500 to 6,000 m. The surface elevation varies between 122 and 344 mBf.



Fig. 28: Location of Gödöllő concession area

² The density of the water considered to be constant, regardless to the temperature for the simplicity of the calculations.

Currently there are 2 HC exploration areas and 3 mining allotments on that area. (Zilahi-Sebess & Gyuricza, 2012c).

Geological settings

The Pre-Cenozoic basement is round about 1,000-1,500 m deep, but the deepest point at the eastern part of the concession area reaches the 3,000 m depth. (Haas et al, 2010).

Upper Triassic sediments can be found settled on the basin, mainly from the Main Dolomite Formation, Dachstein Limestone Formation, , and there are some sequences from the Budaörs Dolomite Formation as well.

The potential geothermal reservoirs, according to Zilahi-Sebess & Gyuricza, (2012c), are as the following:

- Main Dolomite Formation at the east side of Gödöllő,
- The Pre-Cenozoic basement of the eastern side for EGS approach.
- Budaörs Dolomite Formation at Isaszeg,
- Triassic carbonates from the Dachstein Limestone Formation,

Geothermal aspects

Temperature measurement only available until a maximum depth of 1,600 m. According to the existing wells at the concession area, the average geothermal gradient between 0-1,585 m is estimated to be **41.5°C/km**, while the average heat flux is **90-115 mW/m²**. (Zilahi-Sebess & Gyuricza, 2012c)

EGS could be applied from the depth of 2000 m because the Pre-Cenozoic basement is around 1,500 m deep. The expected temperature at 2000 m is **93.4 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$) represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 103.8°C temperature drop stands for 165.7 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **17.4 PJ**.

A conventional hydrothermal systems are above the Pre-Cenozoic basement. This case it is 1000 m and the expected temperature is **52 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ**

exploitable heat energy with a temperature drop of 1°C. 41.5 °C temperature drop stands for 184.9 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **52.1 PJ**.

Geochemical composition

In the deeper Mesozoic and Eocene deposits there are two water types with different origins. Fossil water can be found south of the Balaton (Tóalmás)-line. The total 17,000-39,000 mg/l. At the other side of the line, karst water can be found with a high dynamic water supply (Zilahi-Sebess & Gyuricza, 2012c).

There are only 8 wells, which reached the Pre-Tertiary basement with an average depth of 1,950 m. In total there are 12 wells, deeper than 1400 m, though I found water analysis only in 8 wells. Unfortunately the low number of analysis is not enough to give an extensive geochemical analysis from the area. Though there are two wells with extraordinary values.

B-75 and G-3 wells are located in the middle of the concession area. There are two water analysis in both wells. Table 9 shows the exact measurement data of the wells.

Table 10: Results of the geochemical analysis

Well ID	EOV Y	EOV X	Depth of the well [m]	Depth of the perforation [m]	TDS [mg/l]	Mg [mg/l]	Br [mg/l]	J [mg/l]
B-74	673051	250094	2507	1146-1334	38,967	439	2.9	7.7
G-3	678098	247089	1923	905-1070	34,564	213	-	-
GD-1	679508	248245	1936	1935	24,150	166	-	-

The high dissolved magnesium content makes the area extraordinary, regarding to metal extraction. The average magnesium content from the rest of the wells is 23 mg/l.

3.3.2. Ráckeve

The area around Ráckeve was proposed to be a geothermal concession area in 2014. It is situated in the South-



East corner of Hungary (Fig. 19). The concession area is 449.75 km² from the depth of 2500 to 6000 m. The surface elevation varies between 98 and 147 mBf. Currently there is no right given for HC exploration and there are no mining allotment in HC exploitation on that area (Zilahi-Sebess & Gyuricza, 2014)

Geological settings

. The Pre-Cenozoic basement has an average depth of 2,000-2,500 m under the northern part of the concession area (Haas et al., 2010). The area is situated in the Mid Hungarian Shear Zone (Palotai, 2013). At the southern part there is a pull-apart basin, the so-called Adonyi Basin. The deepest part here reaches the 5,000 m depth. Fig. 20 shows a seismic interpretation from Palotai, 2013. The seismic cross section shows the geological structure with the epoch indicated in the Adonyi Basin.

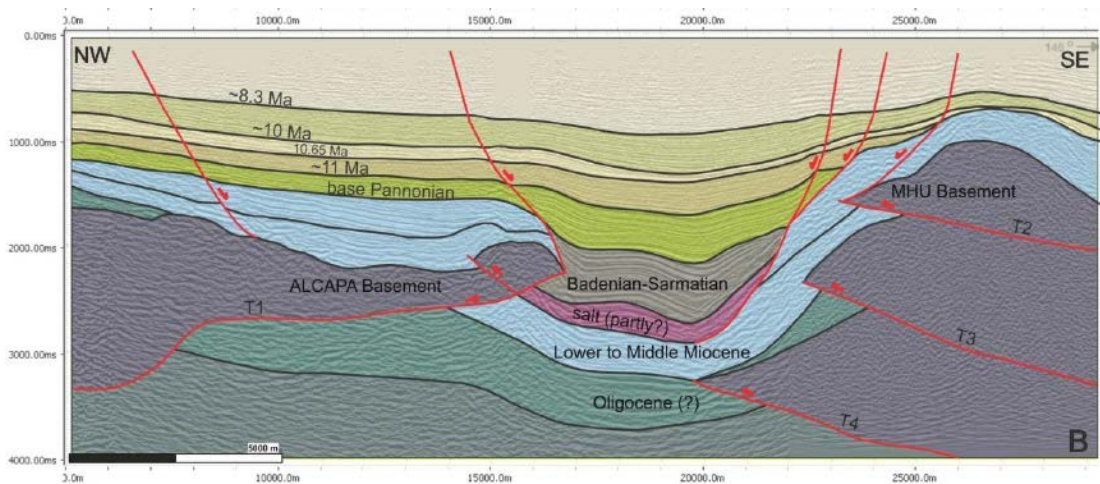


Fig. 30: Interpreted seismic section across the Adonyi Basin (Palotai, 2013).

Though just very few drilling have reached the basin, Upper Triassic carbonates are expected to be the basement rock. (Zilahi-Sebess & Gyuricza, 2014)

Geothermal aspects

According to the existing wells at the concession area, the average geothermal gradient between is around **38 °C/km**, while the average heat flux is **94 mW/m²**. (Zilahi-Sebess & Gyuricza, 2014)

EGS could be applied from the depth of 3000 m because the Pre-Cenozoic basement is around 2,500 m deep. The expected temperature at 3000 m is **124.4 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$) represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 114 °C temperature drop stands for 227.6 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **23.9 PJ**.

Conventional hydrothermal systems are above the Pre-Cenozoic basement. In this case the depth is 2000 m and the expected temperature is **86.4 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ** exploitable heat energy with a temperature drop of 1°C. 76 °C temperature drop stands for 253.9 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **71.6 PJ**.

Geochemical composition

In MBFH I only had access a very limited database on water chemistry. On one hand there are not many deep wells had been drilled at area and on the other and the concentration of dissolved metals is very low. The average Mg content in 4 wells (K-59, Bu-5, K-43, K-45) at 1,200 m depth at range, is 25 mg/l, while the TDS is 1974 mg/l. Ráckeve-1 has the highest dissolved mineral content, with 78 mg/l Mg and 8689 mg/l TDS content.

There are two wells with trace element measurement (Table 10), showing the low metal content.

Table 11: Content of trace measurement

Well ID	Depth of perforation [m]	Li [mg/l]	Cu [mg/l]	As [mg/l]	Ba [mg/l]	Zn [mg/l]	Pb [mg/l]	Br [mg/l]
K-43	1033	0.8	0.13	0.024	0.075	0.75	0.011	1.18

K-45	656	-	0.01	0.026	0.08	-	-	1
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3.3.3. Gádoros

The area around Gádoros was proposed to be a geothermal concession area in 2012. It is situated in the South-East part of Hungary (Fig. 21). The concession area is 419.4 km² from the depth of 2500 to 6000 m. The surface elevation varies between 83 and 95 mBf. Currently 92 % of the area overlaps with HC exploration, but there is no mining lease on that area (Zilahi-Sebess & Gyuricza, 2012b)



Fig. 31: Location of Gádoros concession area

Geological settings

The Pre-Cenozoic basin is expected at the depth of 3500 m (Haas et al., 2010). The basic structural outline of the area, according to Papp et al (1993) is the following:

- The Pre-Neogene basin has NE-SW line of strike, imbricate structure,
- There are at least two extension tectonics related transform faults deeper than 10 km,
- Pannonian or younger sediments does not show any tectonic structure, unlike other sediment at the Great Hungarian Plain, according to seismic and borehole geophysics measurements.

In 1985, tragical steam blow out took place at Fáb-4, Fábiánsebestyén. The accident happened during drilling operation, and caused several casualties. The steam and water mixture was 189 °C, having 35 MPa pressure (Zilahi-Sebess & Gyuricza, 2012b). This disastrous event proved the existence of the high enthalpy geothermal reservoir.

Geothermal aspects

According to the existing wells at the concession area, the average geothermal gradient between is around **45 °C/km**, while the average heat flux is **108 mW/m²**.

EGS could be applied from the depth of 3,500 m because the Pre-Cenozoic basement is around 3,000 m deep. The expected temperature at 3,500 m is **190.4 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$)

represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 180 °C temperature drop stands for 359.46 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **37.7 PJ**.

A conventional hydrothermal systems are above the Pre-Cenozoic basement. This case it is 2.500 m and the expected temperature is **145.4 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ** exploitable heat energy with a temperature drop of 1°C. 135 °C temperature drop stands for 400.9 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **113 PJ**.

Geochemical composition

The water bodies in the Lower Pannonian layers has NaHCO₃ characteristics, with 1500 mg/l Na⁺, 3000 mg/l HCO₃⁻, 520 mg/l Cl⁻ and 5000 mg/l average TDS content. Four well reached the deeper water bodies in Miocene, Mesozoic and Palaeozoic reservoirs. Fáb-4 well reached Mesozoic, while Oros-3 well reached Palaeozoic water bodies. Both of them have similar characteristics. NaCl is the dominating salt, including 9300-1,2000 mg/l Na⁺, 11,900-20,000 Cl⁻ and 26,000-35,000 mg/l TDS. According to geothermometer measurement, the waters comes from 5-6 km deep reservoirs (Zilahi-Sebess & Gyuricza, 2012b).

Got accessed to 22 log books which included water chemical analyses. The average concentrations are 10 mg/l Mg and 9857 mg/l TDS. The highest Mg content was measured in Oros-3 at 2894 m deep with 329.7 mg/l. Thought, this value is not representative since the layer came through an acidizing treatment 7 days before the sample was taken. After 5 month the Mg concentration dropped to 24.6 mg/l, which is common at this area. Even though I did not found specific data about the exact acidification treatment method, it is interesting example about the rule of pH level regarding to solubility. Surprisingly pH modification did not have much influence on the TDS level. TDS was 35,488 mg/l 7 days after the acidification, and after 5 months the TDS dropped less than 3,000 mg/l to 32,590. This case shows that pH modification is a method that could be applied not only at the extraction plant, but insitu, in the geothermal reservoir. This technology is utilized in insitu uranium, gold and copper recovery, which is a technology for in situ solution mining.

3.3.4. Ferencszállás

The area around Ferencszállás was proposed to be a geothermal concession area in 2012. The area is situated in the S-SE corner of Hungary (Fig. 22). The concession area is 101.4 km² from the depth of 2500 to 6000 m. The surface elevation varies between 88 and 78 mBf. Currently there is no right given for HC exploration, but there are 4 mining allotment in HC exploitation on that area (Zilahi-Sebess & Gyuricza, 2012a). Near the concession area there are two major city, Szeged and Makó with 185021 total population (KSH, 2014).



Fig. 32: Location of Ferencszállás concession area

Geological settings

The average depth of Pre-Cenozoic basin is 2,500 m deep, excluding the SW corner of the concession. This part it reaches the 4,000 m at a small area (Haas et al., 2010). The crystalline basin consist of mainly mica-schist and gneiss, resulted by metamorphic events. The upper part of the basin is often fractured, sometimes breccial and weathered (Kőrössy, 2005). The Pannonian sediments (Fig. 23) in the younging order are as follows:

- Békési Fm: conglomerates, calcareous clay bounding,
- Endrőd Fm: marlstone, clay marl,
- Szolnoki Fm: sandstone, siltstone, clay marl,
- Algyői Fm: clay, siltstone, clay marl with sandstone interbedding,
- Újfalusi Fm: wacke with siltstone, clay and marlstone,
- Zagyvai Fm: siltstone, clay and sandstone sequences.

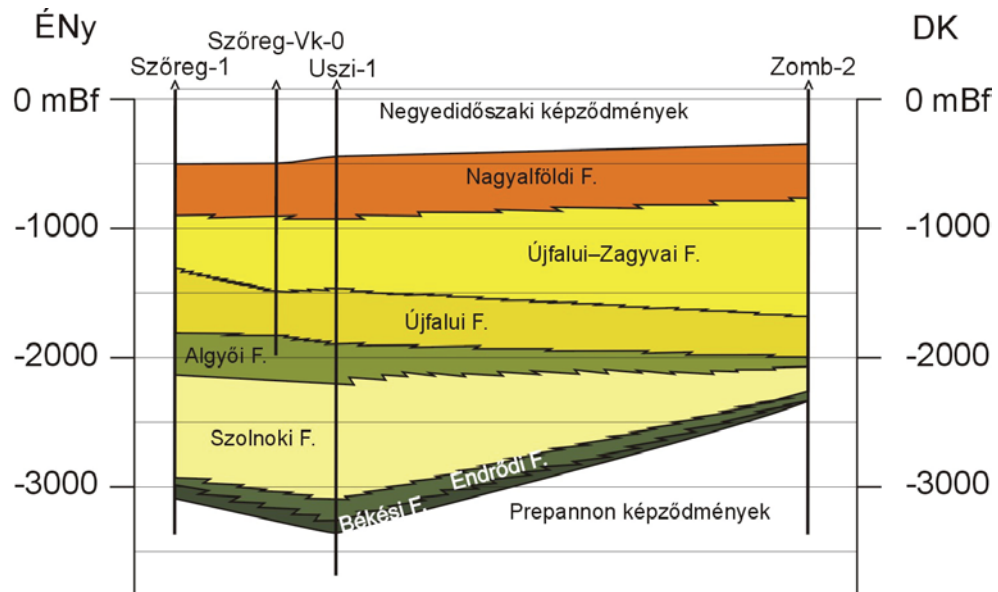


Fig. 33: NW-SE geological section according to drilling data (Zilahi-Sebess & Gyuricza, 2012a)

Geothermal aspects

According to the existing wells at the concession area, the average geothermal gradient between is around **45 °C/km**, while the average heat flux is **100 mW/m²**.

EGS could be applied from the depth of 3500 m because the Pre-Cenozoic basement is around 3000 m deep. The expected temperature at 3000 m is **167.9 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$) represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 157.5 °C temperature drop stands for 314.5 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **33 PJ**.

A conventional hydrothermal system exists above the Pre-Cenozoic basement. In this case it is 2500 m and the expected temperature is **122.9 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ** exploitable heat energy with a temperature drop of 1°C. 112.5 °C temperature drop stands for 350.7 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **98.8 PJ**.

Geochemical composition

The basic water chemistry, including TDS, Cl^- and HCO_3^- , is given in Fig. 32. The samples were taken from different depth.

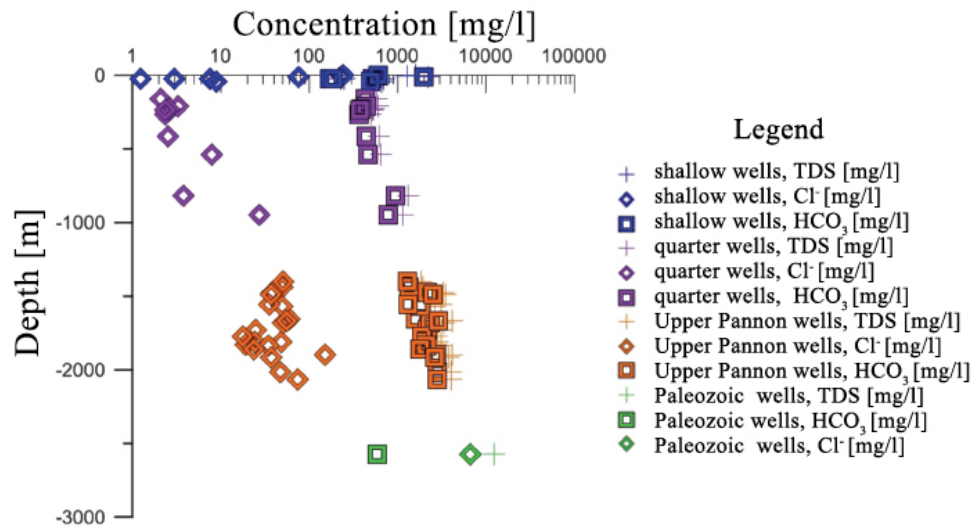


Fig. 34: Concentration values as a function of depth (Zilahi-Sebess & Gyuricza, 2012a)

Further water chemistry data were available from the database of MOL Plc, at Békásmegyer. Secrecy agreement have been established between MOL Plc. and me, so they provide data to my research, but I cannot publish in a way that the information can be located to the exact well.

The number of available water analysis is 90 out of 89 well. Some well had multiple water analyses some had none. The average Mg content is 16.7 mg/l, while the average TDS is 7951 mg/l. The highest Mg concentration is 124.8 mg/l. The potassium content in well Nr. 1 is **324 mg/l**, which is relatively high, compering to the other wells.

3.3.5. Kecskemét

The area around Kecskemét was proposed to be a geothermal concession area in 2012. Kecskemét is located in the Southern part of middle Hungary (Fig. 24). The concession area is 525.3 km² from the depth of 2,500 to 6,000 m. The surface elevation varies between 100.5 and 103 mBf. Currently there is no mining allotment for HC exploitation, but the whole area is HC exploration area (Zilahi-Sebess & Gyuricza, 2012d). Kecskemét, the city itself with



Fig. 35: Location of Kecskemét concession area

112 071 resident (KSH, 2014) is located in the middle of the concession area, with a potential direct heat uptake market.

Geological settings

The Pre-Cenozoic basement is comparatively shallow, around 1,000 m at the SW part of the concession area. Nevertheless it is continuously deepening to the NE side, where the depth reaches the 2,500 m (Haas et al., 2010). The average depth in the centre is 2,000 m.

There is a geological cross section on the area, presented in Fig 36. The Pannonian sediments of the area (Fig. 25) in the younging order are as follows:

- Miocene sediments in the deepest part
- Tótkomlós sequence and Nagykörű division: very thin (<10 m), including schists, clay marl,
- Szolnoki Fm: sandstone, siltstone, clay marl,
- Algyői Fm: clay, siltstone, clay marl with sandstone interbedding,
- Újfalusi Fm: fine and medium grain sandstone with siltstone, clay and marlstone,
- Zagyvai Fm: siltstone, clay and sandstone sequences,
- Quartier sediments (Zilahi-Sebess & Gyuricza, 2012d),

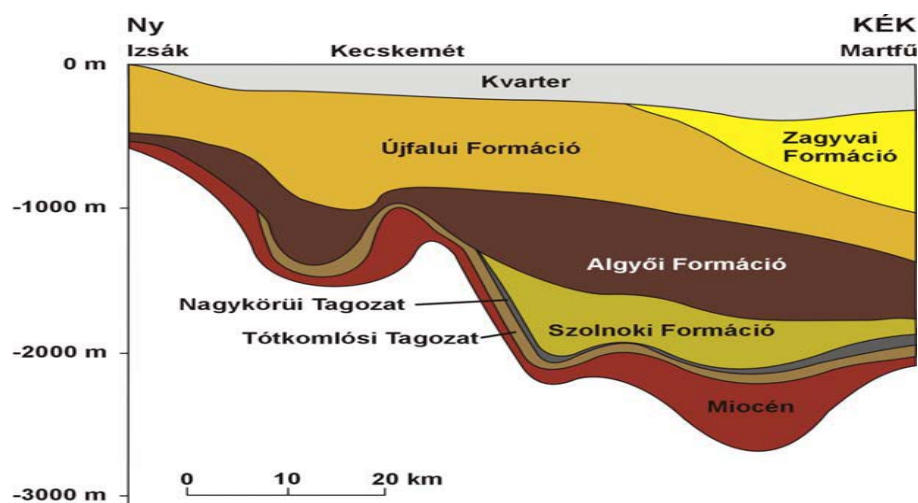


Fig. 36: Geological cross section through the concession area (SW-NE)(Juhász, 1992)

Geothermal aspects

According to the existing wells at the concession area, the average geothermal gradient between is around **45 °C/km**, while the average heat flux is **90 mW/m²**. (Zilahi-Sebess & Gyuricza, 2012d)

EGS could be applied from the depth of 2,000 m because the Pre-Cenozoic basement is around 2,500 m deep. The expected temperature at 2,500 m is **122.9 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$) represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 122.5 °C temperature drop stands for 224.6 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **23.6 PJ**.

A conventional hydrothermal systems are above the Pre-Cenozoic basement. In this case it is 2000 m and the expected temperature is **77.9 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ** exploitable heat energy with a temperature drop of 1°C. 67.5 °C temperature drop stands for 250.6 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **70.7 PJ**.

Geochemical composition

The deeper, Mesozoic water bodies can be divided into two main part. The one from Cretaceous limestone has a 30,000-35,000 mg/l TDS content. The other one has lower TDS content, vary between 15,000-25,000 mg/l and it is associated to Jurassic layers.

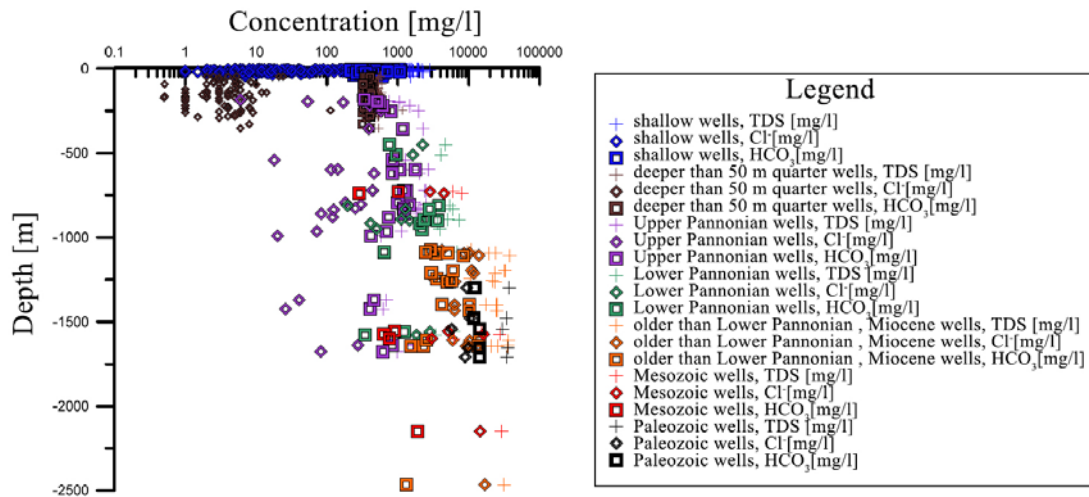


Fig. 37: Concentration values as a function of depth (Zilahi-Sebess & Gyuricza, 2012d)

There are 36, deeper than 1000 m, wells at the concession area (Zilahi-Sebess & Gyuricza, 2012d), but only 28 log book is available at MBFH database. 12 log book contains water analysis, which I could use.

The average Mg content is 44.3 mg/l, while the average TDS is 28079 mg/l. The highest Mg concentration is 111 mg/l in Nk-Ú-5. The highest TDS content is measured at Nk-18 with 56162 mg/l

Outstanding values can be found in well Kecs-D-2 and Nk-Ú-5. The potassium content in the first one is 375 mg/l. The SiO₂ content is 197 mg/l in the second well.

There are no trace element measurement on this area.

3.3.6. Battonya

The area around Battonya was proposed to be geothermal concession area in 2013. Battonya is situated in the South-West corner of Hungary (Fig. 25). The concession area is 358.5 km² from the depth of 2500 to 6000 m. The surface elevation varies between 96.6 and 106.8 mBf. Currently there is no right given for HC exploration, but there are 15 minin allotment in HC exploitation on that area (Zilahi-Sebess & Gyuricza, 2013). Mezőhegyes, Mezőkovácsháza and Battonya are all similar size townships in the corners of the concession



Fig. 38 Location of Battonya concession area

area with 5481, 5952 and 6282 resident. Either of them is potential direct heat uptake market.

Geological settings

The cross section at Fig. 26 describes the Northern part of the Battonya concession area. The Battonya-Pusztaföldvár granitoid ridge continues through the concession area, with a depth of 1000-1500 m (Haas et al, 2010). The Pannonian sediments in the younging order are as follows:

- Endrőd Fm: marlstone, clay marl,
- Szolnoki Fm: sandstone, siltstone, clay marl,
- Algyői Fm: clay, siltstone, clay marl with sandstone interbedding,
- Újfalusi Fm: wacke with siltstone, clay and marlstone,
- Zagyvai Fm: siltstone, clay and sandstone sequences.

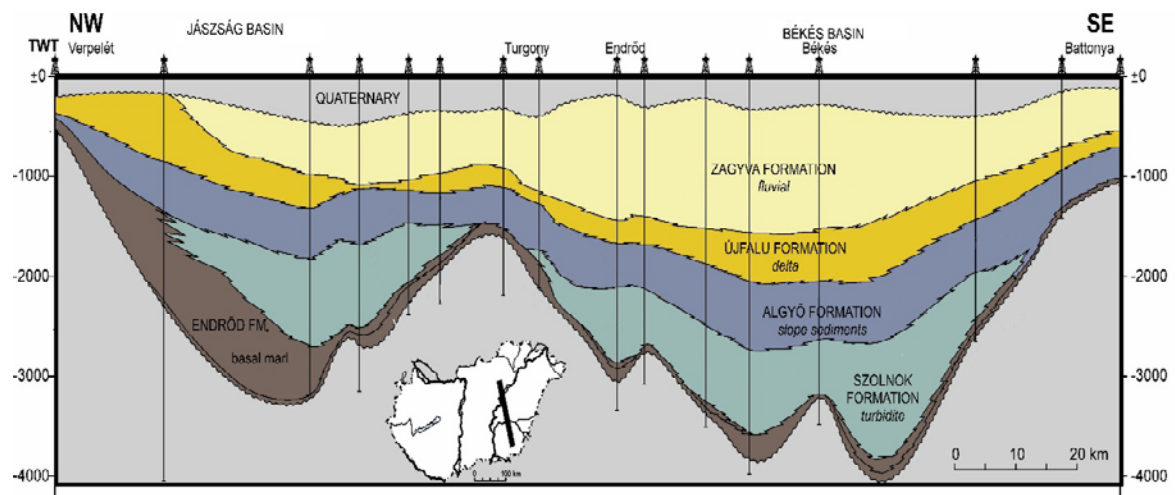


Fig. 39: Cross section near the concession area. (Szamosfalvi, Falus, & Juhász, 2012)

From geothermal exploitation point of view, the Szolnok Formation has an approximate effective porosity of 8% at a depth of 2500 m (Zilahi-Sebess & Gyuricza, 2013), so conventional technologies could be used here for geothermal exploitation. The Battonya-Pusztaföldvár granitoid ridge is expected to have a low porosity but high temperature rock mass, therefore it is a potential EGS filed.

Geothermal aspects

According to the existing wells at the concession area, the average geothermal gradient between is very high, **63 °C/km**, while the average heat flux is **120 mW/m²**.

EGS could be applied from the depth of 1700 because the Pre-Cenozoic basement is around 1,200 m deep. The expected temperature at 1700 m is **117 °C**. According to the previous calculations in Chapter 3.2, **1 km³ of granite block** ($\phi=5\%$) represent **2 PJ** exploitable heat energy with a temperature drop of 1°C. 107 °C temperature drop stands for 213.9 PJ/km³ in total. The void water is only 0.05 km³ from above which represent 10.5 % of the total potential which is **23.4 PJ**.

A conventional hydrothermal system is above the Pre-Cenozoic basement. In this case it is 1500 m and the expected temperature is **105 °C**. **1 km³ of sandstone block** ($\phi=15\%$) represent **2.23 PJ** exploitable heat energy with a temperature drop of 1°C. 94.6 °C temperature drop stands for 350.8 PJ/km³ in total. The void water is only 0.15 km³ from above, representing 28.2 % of the total heat energy, which is **99 PJ**.

Geochemical composition

There are 51 HC wells at the Battonya Concession area, owned by MOL Plc. Secrecy agreement have been established between MOL Plc. and me, so they provide data to my research, but I cannot publish in a way that the information can be located to the exact well.

There are 52 basic water analyses and only 8 measurements about trace elements. My interest was the metal content of the water, but I collected all the water analyses, including the main anion, kation and trace element contents.

In general the Total Dissolved Content (TDS) in the Upper Pannonian sand deposits varies between 1600-4500 mg/l with an average of 3340 mg/l. The TDS in the Lower Pannon sand deposits varies between 3500-21000 mg/l with an average of **12200 mg/l**.

From hydrometallurgical point of view, the area has some interesting aspects, but there are no really high values.

In some wells there were no water analysis, in some others there are more than one at different depths. In total there are 64 data for magnesium content. The average is **32 mg/l**, the highest value is **123.7 mg/l**.

The potassium content in three wells exceeds 300 mg/l, which is a relatively high value. Hungarian mineral waters has two order of magnitude lower average K content (“Vízinform,” 2007).

The lithium content varies between 0.5 and 4.3 mg/l. Li is a target element so it is important for comparison with the other areas.

Table 14 Amount of measured elements

Well nr.	Depth of sampling	Amount of measured elements [mg/l]							
		Li	K	Sr	Ba	Mo	Cu	Be	Ag
1	1193	0.48	53	0.44	0.19	-	0.03	-	0.009
2	1194	2.8	331	5.8	6.3	-	0.16	-	0.035
3	1153	4.3	141	0.5	0.47	0.06	0.05	0.01	-
3	1153	1.4	406	5	2.7	-	0.4	-	-
4	1239	0.53	360	1.4	2.2	-	0.11	-	-
Average		1.9	258	2.4	0.15	-	0.15	-	-

4. Selection of the two most advantageous regions for further investigation

Once the geothermal concession areas are introduced, I am going to compare them, according to the rating standpoints, in order to answer the main questions mentioned in the former chapter.

From the *geological point of view* the examined areas have fairly similar setting, which is general in the Pannonian Basin. Each of them has some km thick sedimentary sequence, including sandstone, marlstone, siltstone, clay and at some areas limestone can be found as well. The depth of the Pre-Cenozoic basement varies between 1000 and 5500 m (Table 15).

Table 15: Depth of the Pre-Cenozoic basement in the concession areas

Depth of the Pre-Cenozoic basement [m]	Gödöllő	Ráckeve	Gádos	Ferencszállás	Kecskemét	Battonya
Minimum	1,000	1,500	3,000	2,500	1,000	1,000
Average	1,500	2,500	3,500	3,000	2,000	1,200
Maximum	3,000	5,500	4,000	4,500	2,500	1,500

The Gödöllő, Kecskemét and Battonya areas have relatively thin sediments above the basement, while the sediments at Ráckeve, Gádos and Ferencszállás have thicker than 4000. The thickest sedimentary sequences can be found at Ráckeve in the Adonyi basin.

The *geothermal features* of the area, like geothermal gradient and heat flux are presented in Table 16.

Table 16: Geothermal features of the concession areas

Geothermal features	Gödöllő	Ráckeve	Gádos	Ferencszállás	Kecskemét	Battonya
Geothermal gradient	41.5	38	45	45	45	63
Heat flux	100	94	108	100	98	120

Battonya has the highest geothermal gradient and heat flux by far, but here the basin is very shallow, therefore there are neither deep wells nor water analysis available from the basement. However, EGS technologies might be applied here. Ráckeve has the least advantageous geothermal features regarding to geothermal gradient and heat flux.

Not only the geothermal gradient but also the depth of the basin were taken into account while calculating the geothermal potential in Chapter 3.3. The calculated geothermal potential is not equal to the exact exploitable heat energy. During my

calculation I assumed ideal conditions, like permeability, water supply and recharge. Since the same methodology was applied in all areas, the calculated geothermal potential (Table 17.) can be used for *comparison purposes*.

Table 17: Geothermal potential of the concession areas

Geothermal potential ³	Gödöllő	Ráckeve	Gádoros	Ferencszállás	Kecskemét	Battonya
max. hydrothermal [PJ]	52.1	71.6	113	98.9	70.7	67.3
min. EGS [PJ]	17.4	23.9	37.7	33	23.6	22.4

Gádoros and Ferencszállás areas show the highest geothermal potential. Ráckeve, Battonya, Kecskemét have medium and Gödöllő has the lowest potential.

The aim of mineral extraction from geothermal brine is to *increase the financial feasibility*. Consequently, for comparison the market values of the potentially produced values are going to be presented (Table 18).

Table 18: Market values of the dissolved metal compounds

Compound	Li ⁴	K ⁴	Mg ⁴	Si ⁵	Cr ⁴
Market value [US\$/T]	6,600	287	2,450	1,852	2,090
Compound	Zn ⁴	Pb ⁴	V ⁴	Ni ⁴	Cu ⁴
Market value [US\$/T]	2,300	2,006	25,000	14,950	6,719

³ Regarding to the geothermal energy relative to the surface temperature (10.4 °C) that is stored by water in a 1 km³ ideal reservoir. $\phi=5\%$ for EGS and $\phi=15\%$ for hydrothermal, according to the previous calculation at Chapter 3.2.3.

⁴ The metal prices are from <http://www.infomine.com/investment/> at 26.10.2014

⁵ The silica price is from <http://www.metalprices.com/> at 26.10.2014

Assume 1 m³/min production rate of geothermal brine. In one year it is 525,600 m³ brine. Consider a 90 % recovery rate from the brine. That case if the concentration is 50 mg/l, the annual potential metal/mineral recovery is 23,652 kg. From each area the most beneficial well had been chosen for the following calculation. The potential metal extraction and its annual market value is introduced in Table 19.

Table 19: Metal extraction potential from geothermal brines and the calculated market value in the examined areas

Area	Metal	Concentration [mg/l]	Production [T/yr]	Annual income [\$]	Total annual income [M\$]
Gödöllő	Mg	439	207.66	508,778	0.51
Ráckeve	Cu	0.13	0.06	413	0.001
	Zn	0.75	0.35	816	
Gádosros	Mg	330 ⁶	156.1	382,444	0.38
Ferencszállás	Mg	128.8	60.9	149205	0.19
	K	324	153.3	43997	
Kecskemét	Mg	111	52.51	128,643	0.2
	K	375	177.39	68,650	
Battonya	K	406	192.05	74,325	0.07

From the table it seems that Ráckeve and Battonya have very low, while Gödöllő and Kecskemét have low potential for metal extraction.

Gödöllő has the highest potential with *0.51 M\$ annual extra income from magnesium extraction.*

Gádosros has a potential *0.38 M\$ annual extra income from magnesium extraction.* Although this value can be reproduced only with acidizing the layer.

⁶ Concentration value after the acidic treatment of the layer

The maintenance costs were not taken into consideration. These costs are highly complex and complicated to calculate and did not fit into this study, therefore I disregarded that part of the project.

Gödöllő and Gádoros have the best geothermal and metal extraction potential. Consequently the answer to the initial question is that *the most benefiting areas for combined heat, power and metal extraction are Gádoros and Gödöllő* out of the 6 examined geothermal concession areas.

5. Conclusion

The overall conclusions based on the findings of my research are as the following:

- Hungary has a great potential for both geothermal energy production and direct heat utilization
- Metal extraction from geothermal brine is a viable technology and results increased financial feasibility and improved geothermal exploitation.
- Ferencszállás, Gádoros and Battonya have the highest geothermal potential.
- *Gádoros Gödöllő* turned out to be the most advantageous areas in terms of geothermal potential and metal extraction.
- acidic treatment of the layer could increase the metal (e.g. Mg) content with one order of magnitude, while the TDS increases inly 10 %
- The potential annual income from the metal extraction at best areas is at the range of 0.3-0.5 million USD.
- Technologies in co-production of geothermal energy and metals require further improvement before its widespread in an industrial scale.

Moreover my plans, regarding the further research on combined heat, power and metal extraction, are:

- continue the research at Gödöllő and Gádoros and develop a virtual combined heat, power and metal extraction project,
- extend the study on all Hungarian geothermal concession areas, including Körmend, Jászberény, Kecskemét, Nagykanizsa, Sarkad, Szilvág, Szolnok and Zalalövő.

6. Summary

The aim of the research is to investigate the applicability of combined heat, power and metal extraction at Hungarian geothermal concession areas. In the first part the study includes a review about geothermal energy and mineral extraction technologies. The second part is about the screening of the chosen concession areas and the selection of the two most beneficial regions for such project.

Geothermal energy, the inner heat of Earth, can be utilized by exploitation from a geothermal reservoir. The resources are accessible by deep drilling operation. Conservative approach is the exploitation of existing geothermal fluid in the reservoir pore space, while non-conservative approach involves hydraulic fracturing and water injection. The produced hot water is used for electricity production and/or direct heat utilization such as district heating, agriculture, bathing, all sorts of industrial usage, etc. As all human activity, geothermal exploitation has an impact on the environment, but these impacts are fairly easy to mitigate.

Due to lithosphere thinning, Hungary has impressive geothermal features, although the geothermal utilization factor in Hungary is not as high as the potential.

Mineral recovery from the geothermal brine is a viable technology, resulting improved function of the geothermal power plant (e.g. reducing scaling) and increasing financial feasibility by the extracted marketable metals. Chemical compounds can be extracted from the brine by either biological approach or physiochemical methods like chemical precipitation and coagulation, ion exchange, membrane and electrochemical technologies and adsorption using active carbon.

Regarding to Hungary, six geothermal concession areas have been investigated related to the applicability of combined heat, power and metal extraction (CHPME), including Gödöllő, Ráckeve, Gádoros, Ferencszállás, Kecskemét and Battonya. In order to decide which areas are beneficial for CHPME, three rating standpoints have been considered. These are geological settings, geothermal aspects and geochemical composition. Gádoros and Gödöllő turned out to have the highest potential for CHPME according to the standpoints. The potential annual income from the metal extraction in the best areas is at the range of 0.3-0.5 million USD, without taking into consideration the maintenance costs.

7. Összefoglalás

A kutatásom célja a magyar, koncesszióra kiírt, geotermikus területek vizsgálata a kapcsolt hő, elektromos áram és fémkinyerési technológia alkalmazhatósága szempontjából. A dolgozat első fele egy irodalmi áttekintés a geotermikus energiáról és az oldatból való fémkinyerésről. A második részben bemutatom a területek kapcsolt hő, elektromos áram és fémkinyerési potenciálját, majd összehasonlítva kiválasztom a két erre a projektre legalkalmasabb területet.

A Föld belső hője, a geotermikus energia hozzáférhető és kitermelhető. A hagyományos értelemben vett készletek a kedvező porozitású forró vízzel telt geotermikus tározók, amik mélyfűrészi technológiával termeltethetők. A nem hagyományos készletek hasznosításánál hidraulikus repesztésre és víz injektálásra kerül sor. A termelt forró víz felhasználható elektromos áram előállítására és/vagy direkt hő hasznosítási célokra, olyan területeken, mint a fűtés, balneológia, mezőgazdaság, különböző iparágat, stb. Mint minden emberi tevékenységnek, a geotermikus energia felhasználásnak is van környezeti lábnyoma, de ezek a behatások viszonylag egyszerűen mérsékelhetők. A Pannon medence vékony litoszférája miatt Magyarország kedvező geotermikus adottságokkal rendelkezik, habár a jelenlegi geotermikus kihasználtságot jelentősen lehetne növelni.

A különböző kémiai komponensek geotermikus oldatból való kinyerése működő technológia. Két fő előnye, hogy csökkenti a geotermikus rendszer igénybevételét, kevesebb só kiválás a kezelt vízből, és növeli a projekt gazdasági megvalósíthatóságát a kinyert fémek értékesítésével. A kinyerést szolgáló technológiák működhetnek biológiai vagy fizikokémiai alapon, mint a kémiai kicsapás és koaguláció, ioncsere, elektrokémiai módszerek, membrán technológiák, vagy aktív szenes eljárások.

Hat magyar, geotermikus koncesszióra kiírt területen vizsgáltam a kapcsolt hő, elektromos áram és fémkinyerési technológia alkalmazhatóságát. Ezek a területek Gödöllő, Ráckeve, Gádos, Ferencszállás, Kecskemét és Battonya városok körül terülnek el. A három számításba vett szempont a terület geológiája, geotermikus adottságok és a vizek geokémiai összetétele. Gádos és Gödöllő bizonyult a két legelőnyösebb területnek ahol a fémkinyerésből potenciálisan előállítható évi bevétel 0.3-0.5 millió USD körül mozog, nem számítva a technológia fenntartási költségeit.

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