MSc Program
Renewable Energy in Central and Eastern Europe

Potential geothermal utilization of depleted oil and gas fields in Slovakia

A Master thesis submitted for the degree of
“Master of Science”

supervised by
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Bratislava, 20.10.2009

Affidavit

I, **Martin Hujsa** hereby declare

1. that I am the sole author of the present Master's Thesis "Potential geothermal utilization of depleted oil and gas fields in Slovakia",
   60 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Date Signature

Abstract

The following study was done as the Master thesis of the NEW ENERGY program, called "Renewable Energy in Central and Eastern Europe" of the Master Course.

Its objective was, above all, to investigate the potential and current state of geothermal energy utilization in Slovakia and to explore possibilities for its further exploitation, specifically electricity production. Moreover, the study focused on geothermal applications in the hydrocarbon business, which utilizes depleted oil and gas fields for the new energy. The co-operation with the OMV Future Energy Fund, GmbH and the Slovak largest hydrocarbon exploration organisation Nafta, a.s. delivers interesting results which could be applied in the reality. The topic firstly focuses on the position of geothermal energy among the other renewables, with its benefits and difficulties. Then it shifts to the history of geothermal utilization with description of the specific conditions in the Slovak market.

The main part of this study is aiming towards calculations of the potential energy, harvested from the existing depleted hydrocarbon boreholes. In fact, two options are considered, one system uses a borehole as a heat exchanger and the other system uses 2 interferenced wells for production and reinjection. The final chapter describes economical analyses of those boreholes.

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List of Abbreviations

Institutions
EC – European Commission
EU – European Union
IEA – International Energy Agency
URSO – Slovakian Regulatory Office for Network Industries

Units
EUR – Euro
GJ – Giga Joule
GWh – Gigawatt per hour
ha – Hectare
J – Joule
m – Meter
m2 – Square Meter
m3 – Cubic Meter
Mio. EUR – Million Euros
T EUR- Tousand Euros
MWe – Megawatt electric
MWh – Megawatt per hour
PJ – Petajoule
s - Second
Sk – Slovak Crown

Terms
COP – Coefficient of performance
DH – District Heating
DPP – Discounted Payback Period
GHP – Geothermal Heat Pump
GSHP – Ground Source Heat Pumps
HEP – Hydro Energy Potential
HPP – Hydro Power Plant
IRR – Internal Rate of Return
LHPP – Large Hydro Power Plant
NPV – Net Present Value
PP – Payback Period
RES – Renewable Energy Source
R&D – Research and Development
SHPP – Small Hydro Power Plant
SPF – Seasonal Performance Factor
TPEC –Total Primary Energy Consumption

Chemical substances
CO2 – Carbon Dioxide
NOx – Nitrogen Oxides
SO2 – Sulphur Dioxide

Symbols

u- Specific energy of water and steam
P- pressure
V- volume
ρ- density

1 Introduction

"Earth's currently and potentially available reserve of geothermal energy is a quantity of astonishing magnitude- vastly greater, in fact, than the resource bases of coil, oil, gas and nuclear energy combined. … Although only a fraction of this geothermal bounty can now be tapped, with innovative technology it will remain available for our descendants long after the last drop of oil is produced"

University of Utah: Geothermal Energy, 2001

1.1 Motivation

Nature has a cycle which always ends at the beginning; rain drops fall back to the sea and then vaporize up to the clouds; autumn leaves go down on the ground, change the consistency to nutritious substance and then come up to the branches of a tree with a new energy...

My motivation is to support and produce electricity within the closed cycle as the nature does. Renewable energy is utilizing limitless energy from the sun, water, wind and Earth. Geothermal resources are lying untapped and contribute to the sustainable development of future electricity production. Geothermal energy improves the energy security around the world and contributes to global climate change mitigation.

Many attributes of geothermal energy, namely its widespread distribution, baseload dispatchability without storage, small footprint, and low emissions, are desirable for reaching a sustainable energy future for Europe. Unfortunatelly, geothermal energy is still costly to go for mass production. The drilling cost covers 60- 70% of total investment costs. Furthermore, geothermal is facing two major problems: high initial investment costs and difficult measurement of energy capacity before the installation. This is caused by undervaluing of the long-term geothermal energy which tends to undeveloped and expensive technology in drilling as well as production.

Oil industry uses affordable drilling and exploration technology driven by mass production. Most of the systems are similar to geothermal uses. Therefore parallel utilization in gas and oil fields for geothermal purposes could reduce the cost for electricity significantly. A parallel co-operation of oil industry in the geothermal business should reduce the main obstacles, the high initial costs and potential energy measurements, which introduce more interest to this sector.

1.2 Objectives

The objective of this research is geothermal potential of depleted gas and oil fields in Slovakia. This work analyses a case study of an oil well for geothermal energy which could motivate involved parties for further approaching.

Nowadays, conserved oil and gas boreholes with reduced oil bed have technical potential to be used as another energy source for electricity and heat production. New technology was rapidly improving its economical efficiency in the last decade. This research is exploring the ability of advanced geothermal systems adapted to hydrocarbon wells with the most updated industrial discoveries. Selection of the hydrocarbon well was performed according to suitable geothermal technology which adapts to existing well conditions. The main part of this research contains the feasibility study of two geothermal systems installed in depleted oil field in the East part of Slovakia. They show technical and economical parameters including detailed technical calculation of its energy potential. The last part of this reseach resumes the viability of the projects with possible improvements in the future.

1.3 Limits of this research

The selection of this research is limited with the amount of boreholes within a property range of Nafta Gbely, a.s.. Nafta Gbely, a.s. is the largest public-private company based in Slovakia, focused on exploration and drilling of gas and oil fields. In fact, the company has the longest history and the largest portfolio of boreholes in the hydrocarbon industry in Slovakia. The ability to cooperate with the selection of the most suitable borehole as geothermal energy source was also an impetus to chose this company. Furthermore, the access to information database was approved.

The choice for the well was not considering viable wells in operation, drilling oil or gas. The aim of the selection was in the range of depleted well for carbon production. Other wells from another companies are not concerned due to lack of information.

The purpose of all the boreholes were solely for hydrocarbon business. This means, all the measurements, tests, exploration and the design of borehole diary were done just for this utilization. Therefore information for geothermal mission like test of permeability, through-flow test or measuring temperatures over a certain period were not included. Furthermore, exploration of boreholes with high quantity of salt brine were not considered financially viable. They were liquidated, which is the case of many boreholes in the east part of Slovakia. Also, the period for exploration was limited due to time-limited licence by the state and Mines office. In summary, all the research in further parts has limits in the information database which is described in each borehole individually avoiding misinterpretation.

1.4 Geothermal energy among the Renewables

The Renewable energy sources (RES) were two decades ago something new, unfamiliar and known as minor resource. Most of the scenarios and forecasts of energy production done by international organisations are not expecting any dramatic progress in RES in the future.

The World Energy Council is perhaps the most respected voice in energy futures. Its Commission has produced reports (1993) that draw upon the expertise of hundreds of people globally to evaluate energy resources and anticipate demand and supply patterns. They anticipate growth in "renewables" until 2025 to take their contribution from about 12.5% to about 20% of energy supply, but foresee no more than 10%, and possibly only 5%, of supply coming from "new renewables," as opposed to wood and hydropower (already at 10%).

The International Energy Agency also makes mid-range energy forecasts (1995, 1996). They anticipate that global energy demand will grow 34-46% from 1993 to 2010 (about 2% annually), 1.4% annually in OECD countries, 0.8% in the FSU, and about 4.0% (IEA, 1996: 1-3). These forecasts assume economic growth at 2.9%, 4.3%, and 5-8% in the three country groupings. Fossil fuels will still supply 90% of commercial energy in 2010, with oil production growing 31-39% between 1995 and 2010, natural gas production growing 34-64%, and solid fuels (including coal and biomass) growing 30%. They see hard coal production growing closer to 50% by 2010. They forecasts stable or rising oil prices, with increases of as much as 50% by 2010.

Neither the WEC nor the IEA foresee significant resource constraints on fossil fuel production prior to the end of their 2010-2020 forecast horizons. Energy forecasts tend to be driven strongly by assumptions about energy resources (fossil fuels only) and costs of energy production. The weaknesses of their analysis lie in (1) their failure to tie the future of oil, and to a lesser degree of gas, to declining global resource bases, which will surely decrease the competitiveness of those energy forms, and (2) the non-existence of new renewable energy forms in their analysis[1].

People were considering the technology in the RES field as a high-tech used solely for aerospace or for scientific purposes which is not economically viable. The high prices of fossil fuel was an driven force for engineers to improve the efficiency and reduce the costs for new renewable technologies like PV modules, geothermal power modules or wind turbines. The competitiveness of RES have been increasing rapidly. In fact, learning curve occurs steeper than for conventional sources.

Today, renewables are still a minor part of energy production but the scenarios of those organisations have changed for more promising future...

There is wind, water stream, sun and heat under the Earth’s crust that can be transmitted to energy. The energy from biomass is also renewable when concerning in

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[1] http://www.ifs.du.edu/assets/help/WebHelp/ifshelp.htm#energy_forecasts.htm, Energy Forecasts, University of Denver

sustainable manner. But this source is applicable to other production as well. Food industry, transportation or construction business uses almost the same sources which increases its consumption and thus bound its capacities and opportunities for utilization.

Wind is besides inappropriate opinion of public one of the most unpredictable renewable energy source. The precision of the wind capability for each month is less exact compare to other resources. Therefore this resource has technical boundary including limints in the area where wind plant could be errected. Similarly, solar energy produces more than 60% of the energy during four summer months from daylight. Furthermore, solar and wind energy are inherently intermittent and cannot provide 24houraday base load without megasized energy storage systems, which traditionally have not been easy to site and are costly to deploy.

Hydroenergy is the most advanced and experienced technology worldwide. It has limitation in technical potential of a country. Huge dam is applicable in very few locations where it might not endanger the environment. Small applications are economically viable for permanent level of stream during all seasons which inclose the potential. On the other hand, hydroenergy form a stable, highly predictable base-load of electricity which is important for securing the grid in controled operation.

Geothermal energy has a huge possibility to increase the share of renewables. The map of geothermal potential shows areas with sufficient geological conditions for installing power plants. In contrary, the reality indicates the difference. There are few power plants in Europe that have been installed and tested on site. Most of them were built last half decade which show how brand new and progressive is this sector. The current production is from established high-enthalpy systems but a large volume of low-enthalpy resources, whose potential is much larger, is still lying unutilized in many countries.

2 History of utilization of geothermal energy

Although geothermal energy is categorised in international energy tables amongst the “new renewables”, it is not a new energy source at all. People have used hot springs for bathing and washing clothes since the dawn of civilisation in many parts of the world. An excellent book has been published with historical records and stories of geothermal utilisation from all over the world (Cataldi et al., 1999).

Electricity is produced by geothermal in 24 countries, five of which obtain 15- 22% of their national electricity production from geothermal energy. Direct application of geothermal energy (for heating, bath ing etc.) has been reported by 72 countries.

By the end of 2004, the worldwide use of geothermal energy was 57 TWh/yr of electricity and 76 TWh/yr for direct use. Ten developing countries are among the top fifteen countries in geothermal electricity production. Six developing countries are among the top fifteen countries reporting direct use. China is at the top of the latter list. It is considered possible to increase the installed world geothermal electricity capacity from the current 10 GW to 70 GW with present technology, and to 140 GW with enhanced technology.

Enhanced Geothermal Systems, which are still at the experimental level, have enormous potential for primary energy recovery using new heat-exploitation technology to extract and utilise the Earth’s stored thermal energy. Present investment cost in geothermal power stations is 2-4.5 million euro/MWe, and the generation cost 40-100 euro/MWh. Direct use of geothermal energy for heating is also commercially competitive with conventional energy sources. Scenarios for future development show only a moderate increase in traditional direct use applications of geothermal resources, but an exponential increase is foreseen in the heat pump sector, as geothermal heat pumps can be used for heating and/or cooling in most parts of the world. CO2 emission from geothermal power plants in high-temperature fields is about 120 g/kWh (weighted average of 85% of the world power plant capacity).

Geothermal energy is available day and night every day of the year and can thus serve as a supplement to energy sources which are only available intermittently. Renewable energy sources can contribute significantly more to the mitigation of climate change by cooperating than by competing[2].

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[2] Ruggero Bertani; GEOTHERMAL ENERGY: AN OVERVIEW ON RESOURCES AND POTENTIAL, 2008

Low-enthalpy geothermal resources are yet to be exploited worldwide for electricity generation, although, they are being utilized presently, in industrialized countries for generating heat. There are a plenty of opportunities almost in every country, applicable not only in volcanic areas. With this credit, new technology can be spread in huge volumes, reaching high production. Then realization is able to be very efficient in manufacturing the technology, as well as in situ application in drilling.

In comparisson, photovoltaic technology is far behind geothermal technology in production increase for the last decade. In 1970, photovoltaics were a cliché market focused on satellites which are feeded by solar energy with this technology. This market was very expensive but enables the development of knowledge to further progress. After the 1990, the costs for photovoltaics production was reduced which trigger the realization in the countries with appropriate solar irradiation. The electricity from this system was still expensive, but due to higher production the market was more competitive. In 1970, with a module price of $ 100, - per Watt, the price of solar electricity was still more than 100 times the price of electricity generated by fossil fuel fired power plants. Since 1970 however the price of modules has come down dramatically to $ 3,- per Watt (€ 1.7,- per Watt) and the end of the price reduction is not yet in sight. New technology like thin-film makes it possible regardless the efficiency of the PV module. This scenario is expected to be very similar also in geothermal technology. The first countries which are applying for geothermal energy had the best technical potential. After the investment costs are reduced, technology is spread to other counties with further recoverable amounts of geothermal energy. Even the history of drilling of hydrocarbons shows a huge progress which is utilized in geothermal systems, the purpose for exploration was primarily for fossil fuel. Therefore there is a chance for next costs reduction in making boreholes, which is more than 70% of total costs for geothermal unit[3], especially in measuring, testing and analyzing the hole for geothermal objective.

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[3] ENGINE, Enhanced Geothermal Network of Europe, Workpackage 5- Deliverable D35

3 Barriers for development of geothermal energy in Europe and Slovakia

Cheap price of raw oil was one of the main obstacles for development of geothermal technology. Up to now, the technology for drilling and producing electricity from this source was not competitive with other sources that were used for many decades. History with full of experience in exploring and drilling on oil and gas fields reduces costs of raw oil to minimum. As the consumption in developing countries expands in huge numbers which deplete existing beds, they have less content of valuable oil, complicated exploration and drilling and thus increase the price. Today, the high-enthalpy resources are competitive with conventional sources. Existing sites vykazuju stable high temperatures with permanent flow leading to interesting economical values.

Recent increases in the cost and uncertainty of future conventional energy supplies are improving the attractiveness of low-enthalpy geothermal resources and EGS in general. In 2006, it received much attention in the USA, since this country wants to secure its electricity supply from domestic resources to reduce its dependence on oil and gas imports, and at the same time reduce its contribution to global warming. These reasons cause a growing awareness of the genuine value and near limitless potential of these practically unused geothermal resources. In this context, it is significant to see the huge geothermal potential of the USA, especially of low-temperature resources which can be economically and technically exploited to cover electricity demand of the USA. If this change occurs, EGS (Enhanced Geothermal System) can become a major electricity source for base-load power generation in the USA by the year 2050[4].

The under-estimation of geothermal energy as a long-term option to provide base-load power, which is in comparisson with other low-emmision options such as wind or solar energy does not require electricity storage systems, has led to slowing down of the development of appropriate technologies to use geothermal resources as a viable option

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[4] D. Chandrasekharam & J. Bundschuh, Low-Enthalpy Geothermal Resources for Power Generation, 2008 CRC Press

to meet the future electricity demand. In fact, evaluation for the cost of electricity produced by geothermal resource was not considered in a whole production cycle which doesn't need expensive storage system.
Also, there was no environmental awareness in the past which led to progress of conventional resources like coal or oil power plants. The climate change is today more understandable and lead politicians to improve legislation for green energy.

Twenty years ago, the electricity market looked completely different in Europe. The grid operators and electricity producers were operated solely by a public body. The high regulation procedures managed by states of European Union blocked to enter private companies into the market. Weak legislation supporting private sector did not cover energy sector sufficiently. There was only public interest with little investment opportunities to third private parties.
Nowadays, the situation has been changed all around the Europe. Liberalization of the electricity market has opened new opportunities and now allows private players to compete with huge but rigid public bodies. Bureaucratic burden was released and business became faster. Utilities are strugling with new regulations as well as new players. The EU directive RES-E 2001/77/ES set up clear targets and legislation supporting companies in renewable energy sector that each country of EU follows. This means that Slovakia commit to increase the production of electricity from renewable sources from present 5% to 12% in 2020. This is a real challenge for the next government, if it remains just 10 more years.

Slovakia has one-sided rather then structurized sources of energy for domestic consumptions compare the standards of European Union. On the other hand, Slovakia has the highest density of gas and electricity grid connection per inhabitant.
The main electricity source in Slovakia is coming from nuclear power plants (54%) with technology that is suitable for Russian uranium. The important role in electricity has also fossil fuel with 30% of total share in electricity production; even Slovakia itself produces less than 1% from local boreholes. The rest of the share with 16% belongs to hydro power plants, primarily in a big scale. If we allocate the energy coming from abroad, which is uranium as a source for nuclear power plants and fossil fuel, we will have more than 80%. This number is even more alarming, if we consider that it is coming from one

country- Russia. Concludingly, the energy roadmap in Slovakia is set up somehow in a wrong way which blocks increasing the shares of local energy sources. This is a robust barrier with political background encouraging only conventional energy reducing possibilities for newcomers in the renewable market. The local renewable energy sector is therefore behind any significant share waiting for its share in 2020...

The Strategy of Energy Security in Slovakia set up in 2007 by the Ministry of Economy[5] shows biomass as the most important local renewable energy source. It was estimated that biomass has about 120 PJ of technical potential. Compare to other sources (solar energy 35 PJ, hydro 22 PJ, geothermal 21 PJ, wind 2 PJ) it is significantly high. In fact, biomass is in this way overestimated without considering stable delivery. Moreover, there are difficulties with ownership of the forests that are fragmented due to the cadastre system over a history. On the other hand, the rest of the renewables are underestimated, including geothermal energy which has certainly higher potential. The reason for this is that local researchers were not counting with low enthalpy, but just high temperature beds which are in Slovakia limited. If they would calculate with present technology for low enthalpy geothermal sources, they have much higher numbers.

4 Modern use of geothermal energy

Electricity has been generated commercially by geothermal steam since 1913, and geothermal energy has been used on the scale of hundreds of MW for five decades both for electricity generation and direct use. The utilisation has increased rapidly during the last three decades. Geothermal resources have been identified in some 90 countries and there are quantified records of geothermal utilisation in 72 countries.

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[5] Stratégia energetickej bezpečnosti Slovenskej republiky s výhľadom do roku 2030, materál MH SR , november 2007

Electricity is produced by geothermal energy in 24 countries. Five of these countries obtain 15-22% of their national electricity production from geothermal (Costa Rica, El Salvador, Iceland, Kenya and the Philippines).

In 2004, the worldwide use of geothermal energy was about 57 TWh/yr of electricity, and 76 TWh/yr for direct use. The installed electric capacity in 2004 was 8,933 MWe. The installed capacity for direct applications in 2004 was 28,268 MWth. Figure 1 shows the installed capacity and the geothermal energy in the different continents in 2007.

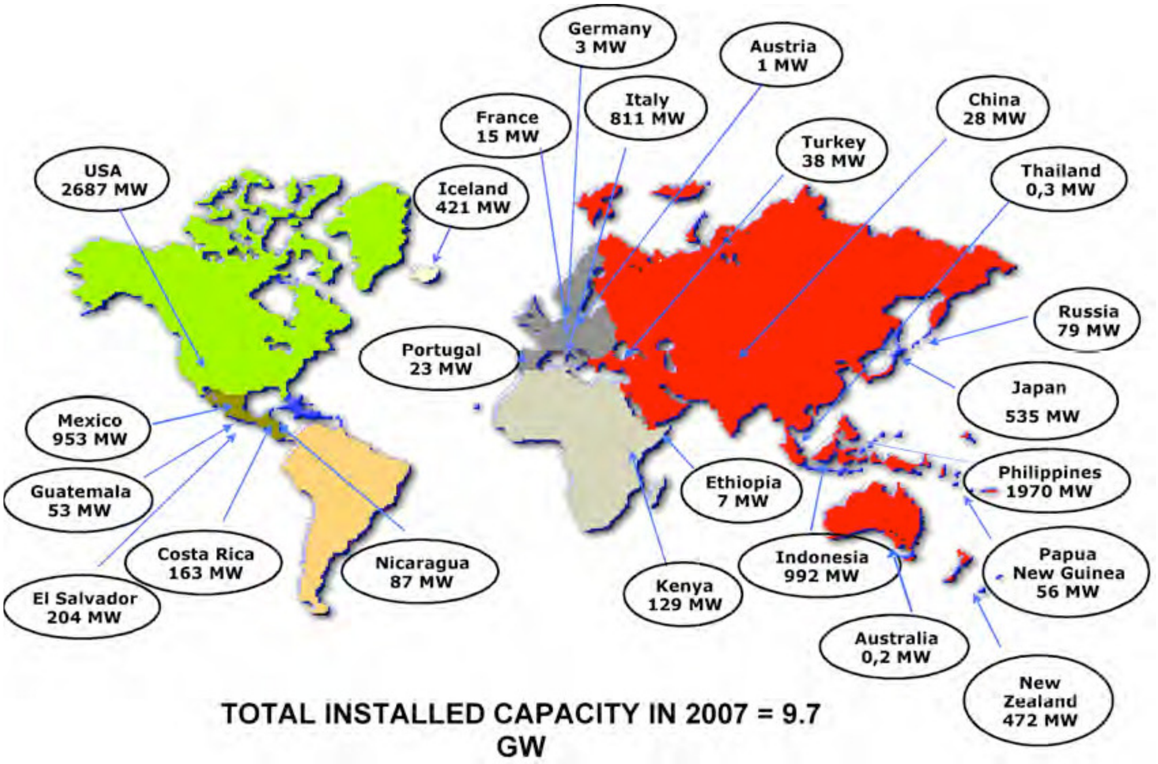

Figure 1Installed capacity for electricity production in 2007 in different countries (Bertani, 2007).

Table below shows some latest geothermal power plants built in Europe. During the last decade, the development of new power plants has significantly increased.

Location	Project/ Company name	MWe	Temp C	Depth m	Circ. l/s	Technology
France, Soulz	HDR Project Soultz	1.5	200	5000	35	ORC CRYOSTAR, air cooling ORMAT
Austria, Bad Blumau	RognerHotel & Spa	0.25	104		31.5	ORMAT 250kW binary plant, air
Germany, Unterhaching	Geothermie Unterhaching	3.36	120	3350	150	Kalina Siemens
Germany, Neustadt Glewe	Erdwärme-Kraftwerk Neustadt-Glewe	0.21	98	1780	30.6	ORC 2 pumps, air
Germany, Landau in der Pfalz	geo x GmbH	3	160	3000	65	ORMAT
Germany, Munchen Riem	SWM	9	93	3000	60	Kalina
Germany, Sauerlach	SWM	8	130	4500	240	Kalina

Table 1 Low enthalpy geothermal power plants in Europe

5 Geothermal technology

In most countries, the potential of low-enthalpy resources especially, did not receive enough attention. The main reason for not developing these resources for commercial exploration is that they are not considered as economically viable for electricity generation. Although, this has been true in the past, technological advances made in the field of heat exchangers and drilling methods in the last decade allow geothermal fluids with temperatures as low as 74 C to be used for electric power generation.

So modern use of geothermal energy includes not only direct heating uses such as process and space heating, but also indirect uses like heating water into steam to drive turbines for electrical production.

Geothermal resources unrelated to volcanoes can be divided into four types:

a) Resources related to deep circulation of meteoric water along faults and fractures;

b) Resources in deep high permeability rocks at hydrostatic pressure;

c) Resources in high porosity rocks at pressures greatly in excess of hydrostatic (i.e. "geopressured");

d) Resources in hot but dry (low porosity) rock formations.

These four types are in fact end members, with most natural systems displaying some intermediate characteristics. All these, with the exception of type c), can also be associated with volcanic activity. Types c) and d) are not commercially exploited as yet[6].

Currently, only hydrothermal resources are in wide use. The remaining three resources are still in the initial stages of development.

Type b) is probably the most important type of geothermal resources that is not associated with young volcanic activity. Many regions throughout the world are characterized by deep basins filled with sedimentary rocks of high porosity and permeability. If these are properly isolated from surface ground water by impermeable strata, the water in the sediments is heated by the regional heat flow. The age of the sediments makes no difference, so long as they are permeable. The geothermal reservoirs in the sedimentary basins can be very extensive, as the basins themselves are commonly hundreds of km in diameter. The temperature of the thermal water depends on the depth of the individual aquifers and the geothermal gradient in the area concerned, but is commonly in the range 50 to 100°C (in wells less than 3 km deep) in areas that have been exploited (such as the Paris basin in France, the Pannonian basin in Hungary, the Williston Basin in Montana, North Dakota, USA and several areas in China). Geothermal resources of this type are rarely seen on the surface, but are commonly detected during deep exploration drilling for oil and gas.[7] This formation is seen in Slovakia and thus is for discussion in further parts.

To be viable for exploration, these systems should be accessible at reasonable depths with sufficient geothermal fluids to sustain long productivity. With high advancement

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[6] International Geothermal Association

[7] Ingvar B. Fridleifsson , Ruggero Bertani, John W. Lund; „The possible role and contribution of geothermal energy to the mitigation of climate change“; IPCC Geothermal 11 February 2008

made in heat exchanger and drilling technologies, EGS may be able to provide low-enthalpy fluids at shallow depths in all countries.

5.1 Enhanced Geothermal Systems

In general terms, geothermal energy consists of the thermal energy stored in the Earth's crust. Thermal energy in the earth is distributed between the constituent host rock and the natural fluid that is contained in its fractures and pores at temperatures above ambient levels. These fluids are mostly water with varying amounts of dissolved salts; typically, in their natural *in situ* state, they are present as a liquid phase but sometimes may consist of a saturated, liquidvapor mixture or superheated steam vapor phase. The amounts of hot rock and contained fluids are substantially larger and more widely distributed in comparison to hydrocarbon (oil and gas) fluids contained in sedimentary rock formations underlying the Vienna basin in the western part of Slovakia.

The source and transport mechanisms of geothermal heat are unique to this energy source. Heat flows through the crust of the Earth at an average rate of almost 59 mW/m^2. The intrusion of large masses of molten rock can increase this normal heat flow locally; but for most of the continental crust, the heat flow is due to two primary processes[8]:

1. Upward convection and conduction of heat from the Earth's mantle and core, and
2. Heat generated by the decay of radioactive elements in the crust, particularly isotopes of uranium, thorium, and potassium.

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[8] Massachusetts Institute of Technology; The Future of Geothermal Energy; 2006

Local geologic and tectonic condition play an important role in determining the location and quality of a particular resource. Moreover, it is a depth and position of a borehole as well as chemistry and temperature of a liquid. All those parameters are commissioned during geological survey. Most of the geothermal power plants are placed in regions with high heat flow, only in tectonic plate boundaries with geologically recent volcanic events. In fact, there is limited number of location which has these geological parameters. It is wrong public attitute, that other regions would have expensive extraction methods for receiving the heat flow on the surface. Thermal energy is transferred by transport processes in porous or fractured regions of rock and conduction through rock itself. The heat flow processes spread the heat under the crust in regions with no evidence of any geological activities.

6 Geological structure of Slovakia

The relief of Slovakia features two distinct geological and geomorphological formations: the Carpathian Arc and its adjacent lowlands. It was shaped by young tectonics, Tertiary volcanism, glacial sculpturing as well as peri-glacial, glacio-fluvial and fluvial processes.

The geologico-morphological conditions in the lowlands are affected particularly by less consolidated sediments, primarily sand, gravel and clays. Lowlands are former marine basins filled by silicoclastics - friable sandstone/sand, siltstone/silt, gravel/conglomerate with a maximum thickness of several thousand meters.

Tectonic processes and the geological composition also substantially affect the relief of mountain massifs. As a result, three arch-shaped zones may be distinguished in the mountainous area of Slovakia: a zone of Flysh Belt along the northern margin of the Carpathians, a group of central core mountain ranges in the middle, and several volcanic ranges on the southern periphery of the Carpathians[9].

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[9] http://www.ecosystems.sk/pages/geo.html, 27.10.2009

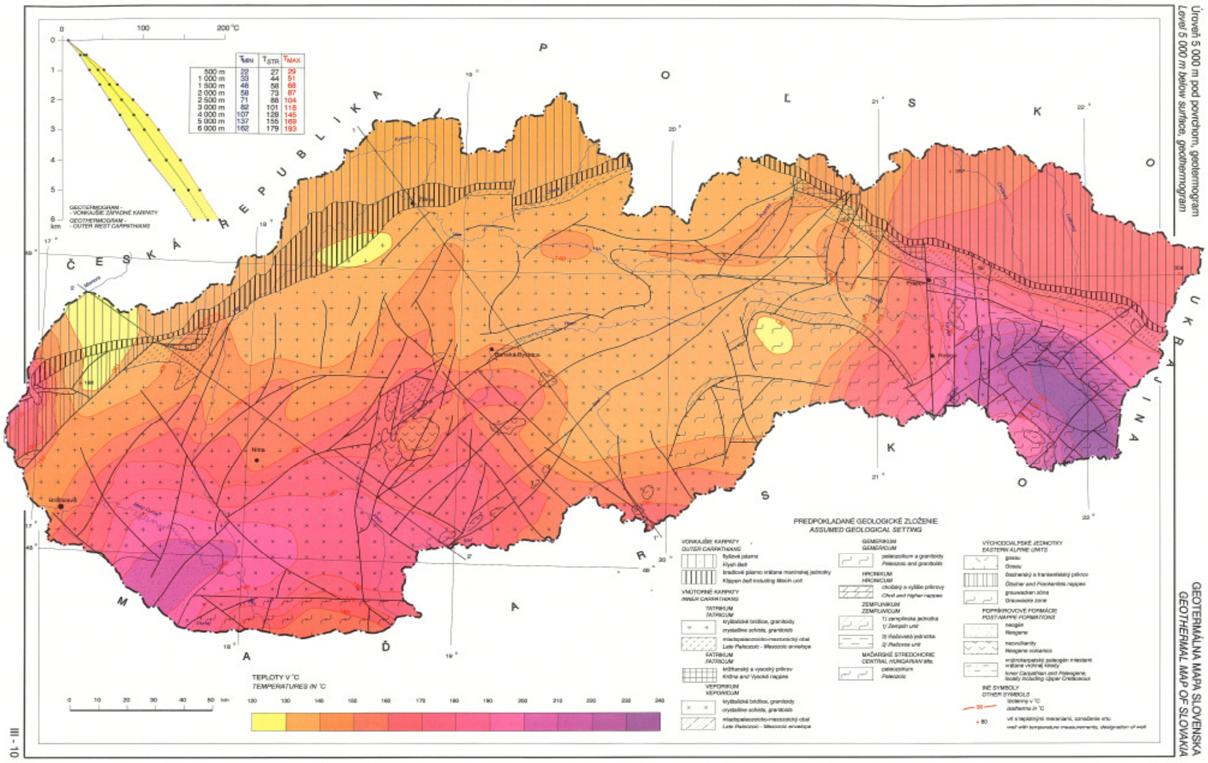

Figure 2 Geothermal map of Slovakia, Geothermogram level 5000m below surface

Hydrocarbon exploration in Eastern Slovakia has revealed very interesting data on geothermal temperatures and formation pressures. The Neogene basin represents one of the highest geothermal temperature basins in the West Carpathians. The temperatures in its central part are approximately 150 ºC at 3000m depth, and reach 209 ºC at 4000m. A moderate temperature area is represented by the Central Carpathian Palaeogene, where only 121 ºC is reached at a depth 5000m. Formation pressures, in both horizontal and vertical directions, display great dispersion from anomalously low (50- 60%) to extremely high (80- 90%) proportions of hydrostatic pressure[10].

The anomalous behaviour of the Neogene basin is basin is not only manifest in this particular area, but also in the West Carpathians as a whole. The highest measured heat flow is 126.4m.W/m² while the average thermal flow is 50- 60 ºC/km.

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[10] Magyar J., Rudinec R.; Temperature-pressure relations in Eastern Slovakia; Nafta Gbely, a.s. PTZ Michalovce

7 The selection of the most appropriate borehole

It should be noted, that the area of exploration made by Nafta Gbely, a.s. was primarily focused for hydrocarbon drilling. Therefore not all the surface of Slovakia was determined. From the point of geothermal utilization, Eastern Slovakia has better opportunities as the western part. In fact, Vienna basin has low geothermal temperatures.

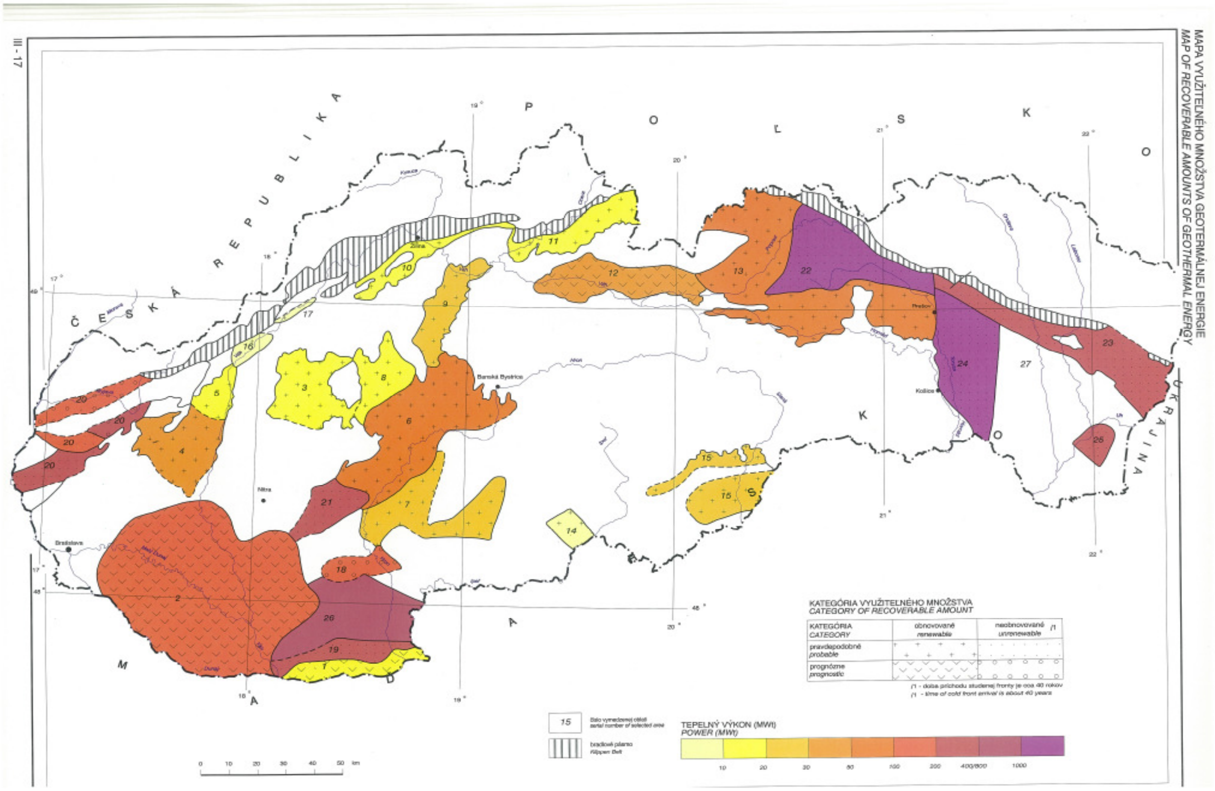

Figure 3 Map of recoverable amounts of geothermal energy

Among all the boreholes drilled during the history of Nafta Gbely, a.s., there were 6 boreholes that sufficiently meet the criterias for geothermal purposes. Those criterias were:

- Temperature gradient above 80 ºC
- Technically available borehole

- Perspective geological reservoirs
- Available data

Most of the boreholes are located in the Eastern part of Slovakia, one is from Western Slovakia. All the available boreholes were consulted with Dr. Polesňák and Dr. Magyar, which are geologists in Nafta, a.s..

Borehole	**Location**	**Geothermal source**	**Depth**	**Tempt**	**Diameter on the bottom**	**Actual status**
Kosice	Eastern SK Basin, near Košíce	Mezozoikum	3250	145	NA	liquidated, prepared for operation
Kapusianske Klacany 28	Eastern SK Basin, near UK borders	Paleozoikum	1812	110	TžK 5 1/2´´	working, interefence between 28 and 29
Kapusianske Klacany 29	Eastern SK Basin, near UK borders	Paleozoikum	2100	101	TžK 5 1/2´´	working, interefence between 28 and 29
Michalovce 4	Eastern SK Basin near Michalovce	Neogene	2300	87	TžK 5 1/2´´, ST 2 3/8´´ Paker Baker A3	liquidated, interefence between 4 and 12
Michalovce 12	Eastern SK Basin near Michalovce	Neogene	2300	87	TžK 5 1/2´´	liquidated, interefence between 4 and 12
Velke Kapusany 8	Eastern SK Basin near Veľké Kapušany	Neogene	3490	145	TžK 6 5/8´´	liquidated
Trebišov 11	Eastern SK Basin Trebišov	Neogene	2475	110	NA	in good condition, revitalized
Secovce 5	Eastern SK Basin near Sečovce	Neogene	1937	114	TžK 6 5/8´´	liquidated, hydropotential
Gajary	Vienna basin near Malacky	Neogene	4250	100	OTIS Paker 6 5/8´´	active

Table 2 Selected boreholes by Nafta, a.s. Sources: Geothermal Source: Magyar; Perspektívne geotermálne územia v neogéne a podloží Východoslovenskej panvy; 2001-2008; Depth, Temperature: Temperature gradient curves by Magyar, Polesnak.

7.1 Analyses of selected boreholes

After the selection of the most appropriate boreholes was done, it is necessary to do analyses of each borehole. In fact, analytical research describes the boreholes more in details with focus on geological conditions. This will bring more light into the geological structure which is important for risk management. If similar analogy between the paired boreholes is observed (Michalovce, Kapusianske Klacany), there is a high potetial of one geothermal lozisko, which could be used for injection and reinjection of working fluid. Concludingly, decision for choosing the cycling system under the ground is determined. Unfortunately, not all information was available for all of the boreholes.

For analyses, there were these characteristics observed:

A) Temperature gradient

B) Mineralization and pH of water

C) Stratigraphy.

Temperature gradient of each borehole was compared with generalized Figure 1 containing curves with different thermal fields. Numerous accurate temperature data from all geological surveys enables Nafta, a.s. to develop models of predicted geothermal energy exploitation in some areas. Possible sources are either from original thermal water flow or heat exchange with hot dry rock.

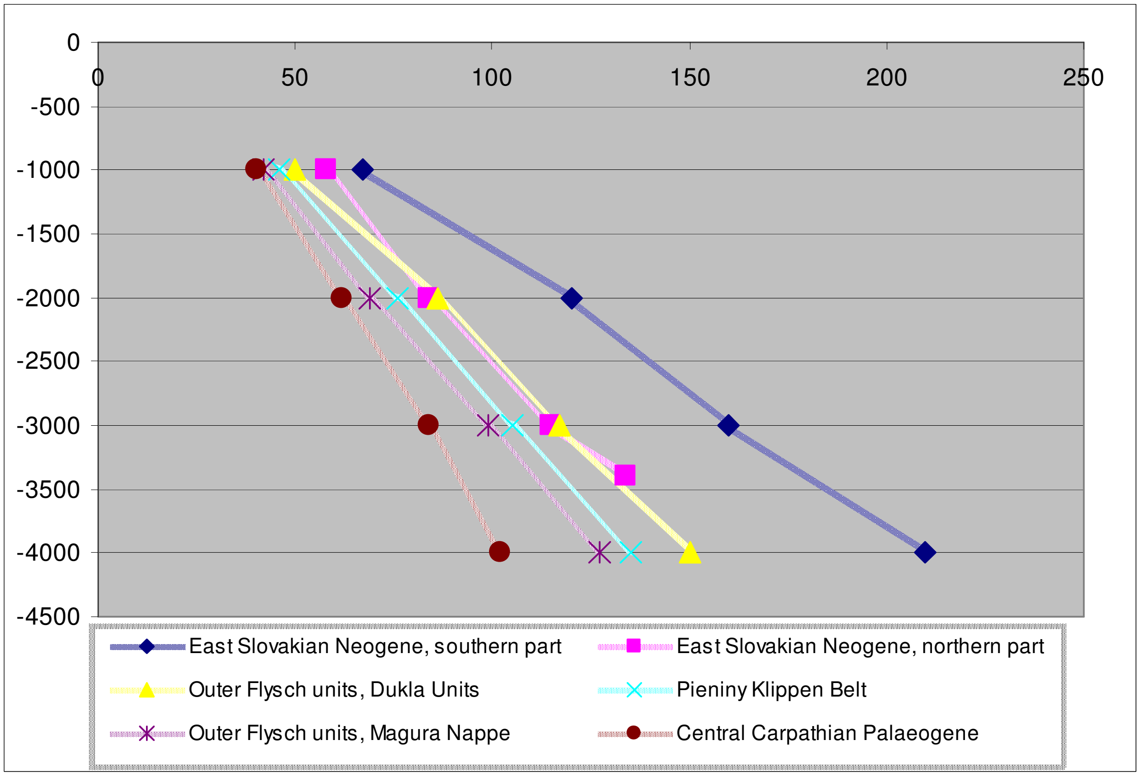

Figure 4 Magyar J., Rudinec R.; Temperature-pressure relations in Eastern Slovakia; Nafta Gbely, a.s. PTZ Michalovce

Under these circumstances, there were selected boreholes added into the Figure 4. This shows us boreholes which are similar to generalized curves in particular geological areas. The vertical distribution of the temperature field shows that the individual units under investigation may be arranged according to increasing temperature as follows: East Slovakian Neogene, Dukla Unit, Pieniny Klippen Belt, Magura Nappe and Central Carpathian Palaeogene.

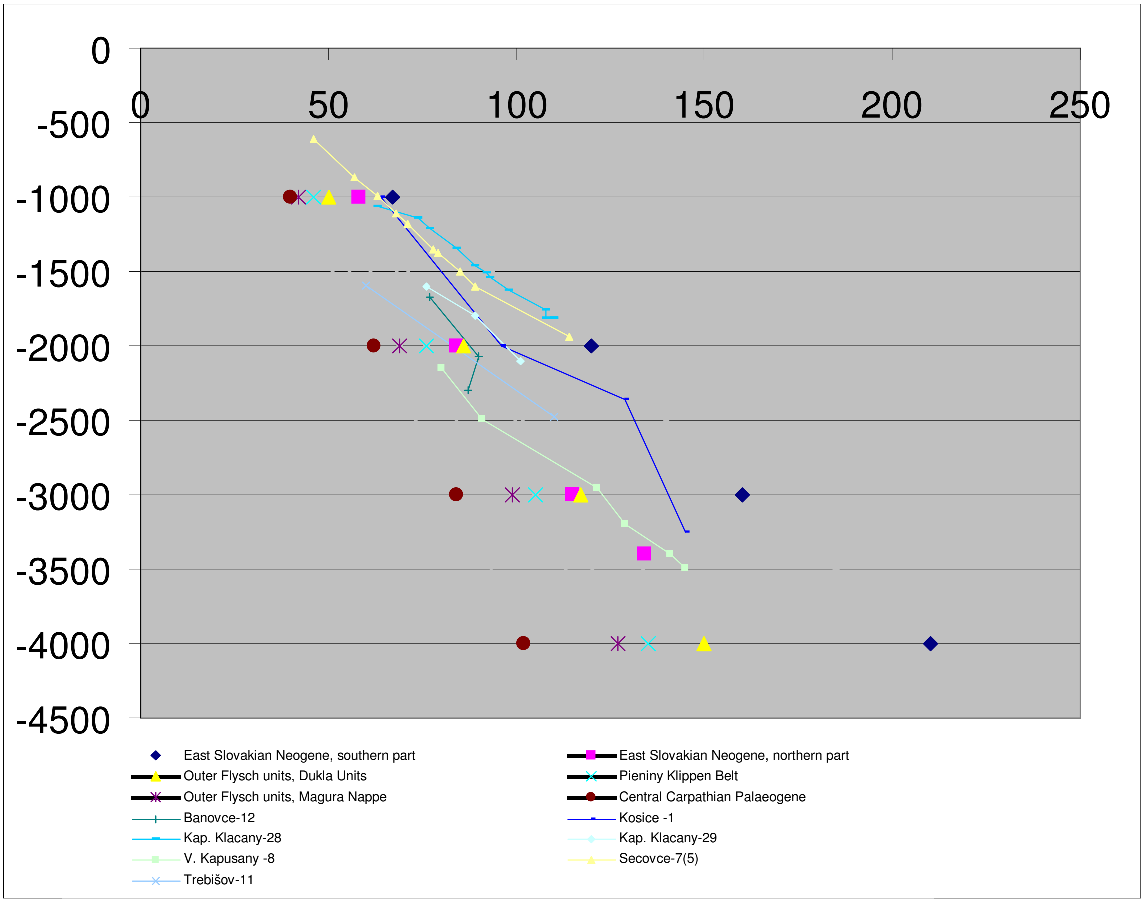

Figure 5 Selected boreholes with temperature gradient curves

From the Figure above, Kapusianske Klacany 28 seems to have very similar temperature/depth characteristics with East Slovakian Neogene, southern part. Geographically, Kapusianske Klacany 28 is located on the southern part of Neogene which could confirm similar geological structure. In addition, it is necessary to compare it with other characteristics. Velke Kapusany has the same temperature gradient with Pieniny Klippen Belt till certain depth of 2500m. Then it turns to more warm areas between the south and north East Slovakian Neogene. The rest of the boreholes are geographicaly located in the area of East Slovakian Neogene and have the same curves as generalized curves which do not submit any significant temperature anomalies.

Mineralization and pH of water were analyzed from available borehole diaries. Some of the information was not available due to any measurements *in situ.* The table below shows standard values with any significant anomalies. Mineralisation has values between 11000 and 20 000mg/l which identifies mild saltiness (about 1100kg/m3). A pairs of wells (Kapusianske Klacany and Michalovce) have very similar values which prove its interferences.

Borehole	Depth range	Water mineralization Phi value [mgl-1]	Water pH Phi value
Kosice		na	na
Kapusianske Klacany 28	1300-2200	27814	7.45
Kapusianske Klacany 29	1400-2100	19895.57	7.23
Michalovce 4	1300-2200	10920.766	7.41
Michalovce 12	1300-2200	10672.857	7.26
Velke Kapusany 8		na	na
Trebišov 11		na	na
Secovce 5	0-500	15772.6	6.7
Secovce 5	500-1800	23881.46	7.8
Gajary		na	na

Table 3 Table of mineralization for the boreholes (Source: Borehole diary)

The table below indicates stratigraphy of each borehole. Most of the geothermal valuable boreholes come from upper baden with high temperature gradient, located in the east part of Slovakia

Borehole	Depth [m]	Stratigraphy
Kosice-1	3250	Trias, bedrock
Kapusianske Klacany-28	1812	Bottom sarmat
Kapusianske Klacany-29	2100	Bottom sarmat
Michalovce-12	2300	Upper baden- last.s
Michalovce-12	2300	Upper baden- last.s
Velke Kapusany-8	3490	Upper baden- last.s
Trebišov-11	2475	Upper baden- last.s
Secovce-7(5)	1937	Upper baden - klč.s.
Gajary	4250	Vienna basin

Table 4 Stratigraphy of selected boreholes

There has been analyzed the interferences of neighouring boreholes by exploitation of natural gas. If there was interference in between the wells, the level of underground water was dropped during the exploitation. As a result, there has been interference identified between the boreholes Michalovce 4 -12 and Kapusianske Klacany 28 – 29. Further analyze through the seismicity was not applied due to different core business of Nafta, a.s..

8 Method of exploitation of existing boreholes as heat exchanger

This research analyses two ways for exploitation of the existing boreholes. First one uses solely one well, where circulation flows through one pipe inside the borehole. The second system uses more complex technology with at least two wells which one is used as for production and other for reinjection of cooled fluid.

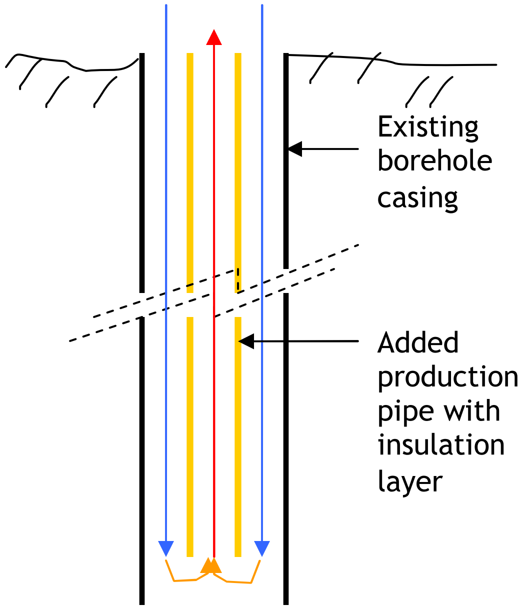

Figure 6 Single borehole heat exchanger

One well system, another word heat exchanger, is primarily limited by diameter of existing casing which reduces the flow of geothermal fluid. Diameter of the tube needs to be analyzed for receiving the best efficiency. In fact, if tube has too large diameter, there is a small volume between the tube and casing. Also, the velocity of the fluid flowing through the pipe has to be studied. If it is too fast, the fluid is not sufficiently heated and if the velocity of the fluid is slow, here is weak flow rate for the production. Therefore thermal flux needs to be calculated with a result of optimal velocity. The fluid which flows into the pipe is pumped by circulation pump and released between the pipe and casing as heated working fluid with no reinjection back to the aquifer. The power of the pump and thermal flux is calculated in the following section.

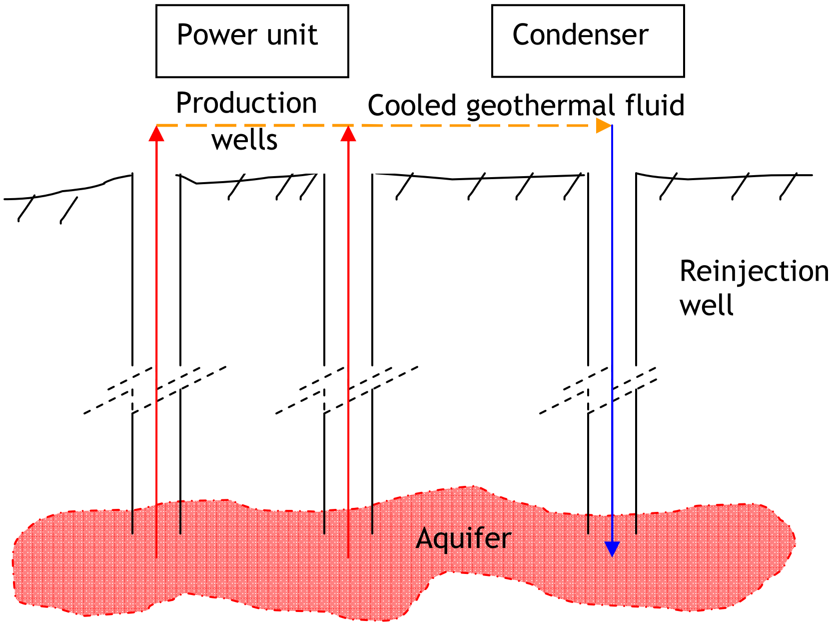

Figure 7 Example of 2 production wells and 1 reinjection well

The system is utilizing one or more production wells and one well for reinjection. They need to meet a primary condition which is one aquifer, where all the wells are connected by one bed. Therefore interference measures among the wells require positive results, which mean they are connected. When those boreholes were exploited, the interference was measured according to levels of liquid inside the borehole. This system has much larger energy capacities due to higher volume of working fluid, compare to the first system. Also, it demands more complex and expensive analyses of energy resource exploration. Thermal, electrical, magnetotelluric, magnetic, seismic and gravity surveys are a few of the methods comonly employed for geothermal exploration.

8.1 Calculation of the pressure drop of the heat exchanger

The selection of boreholes for single well system as heat exchanger was done according to the largest diameter of casing (except pairs of wells). Velke Kapusany and Secovce has been chosen with diameter of casing 6 5/8“ (168.3mm) on the bottom.

Borehole	Location	Geothermal source	Depth	Tempt	Diameter on the bottom	Actual status
Velke Kapusany 8	**Eastern SK Basin near Veľké Kapušany**	**Neogene**	**3490**	**145**	**TžK 6 5/8´´**	**liquidated**
Secovce 5	**Eastern SK Basin near Sečovce**	**Neogene**	**1937**	**114**	**TžK 6 5/8´´**	**liquidated, hydropotential**

Table 5 Table of possible boreholes as heat exchangers

The circulation of the working fluid is forced through the gap between the casing and tubing which needs a pump with certain power output. Following calculation and table shows, how to deal with the pressure drop. For calculation the pressure drop, we need to have these variables: depth of the well L, internal and external diameter of tubing D, internal diameter of casing, density and viscosity of working fluid and flow Q, which was set up from 3 to 20m³/h.

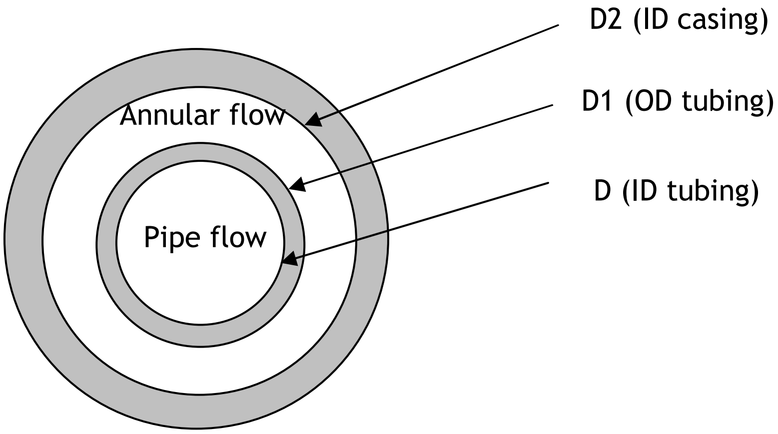

Figure 8: Horizontal section through the pipe and casing of a well.

		Pipe Flow	Annular Flow
	Relation shear stress/shear rate	$\tau = \mu\left(-\frac{dv}{dr}\right)$	
LAMINAR	Average velocity	$v = \frac{4Q}{\pi D^2}$	$v = \frac{4Q}{\pi (D^2_2 - D^2_1)}$
	Reynolds number	$N_{Re} = \frac{\rho v D}{\mu}$	$N_{Re} = \frac{\rho v 0.8165 (D_2 - D_1)}{\mu}$
	Frictional pressure drop	$P_f = \frac{2f\rho Lv^2}{D}$	$P_f = \frac{2f\rho Lv^2}{0.8165 (D_2 - D_1)}$
	Fanning friction factor	$f = \frac{16}{N_{Re}}$	$f = \frac{16}{N_{Re}}$
	$N_{Re(c)} = 2{,}100$		
TURBULENT	Average velocity	$v = \frac{4Q}{\pi D^2}$	$v = \frac{4Q}{\pi (D^2_2 - D^2_1)}$
	Reynolds number	$N_{Re} = \frac{\rho v D}{\mu}$	$N_{Re} = \frac{\rho v 0.8165 (D_2 - D_1)}{\mu}$
	Friction pressure drop	$P_f = \frac{2f\rho Lv^2}{D}$	$P_f = \frac{2f\rho Lv^2}{0.8165 (D_2 - D_1)}$
	Fanning friction factor	$f = 0.057(N_{Re})^{-0.2}$	$f = 0.057 (N_{Re})^{-0.2}$

Table 6 Table for pressure drop calculation (Source: Schlumberger D., Cementing Technology, Nova Communications Ltd, London 1984)

If the Raynolds number is less than 2100, than the fanning friction factor and pressure drop is calculated for laminar flow.

Laminar flow, sometimes known as streamline flow, occurs when a fluid flows in parallel layers, with no disruption between the layers. In fluid dynamics, laminar flow is a flow regime characterized by high momentum diffusion, low momentum convection, pressure and velocity independent from time. In fluid dynamics, turbulence or turbulent flow is a fluid regime characterized by chaotic, stochastic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time[11]. Our caclucations shows the values less than 2100, thus the flow is turbulent.

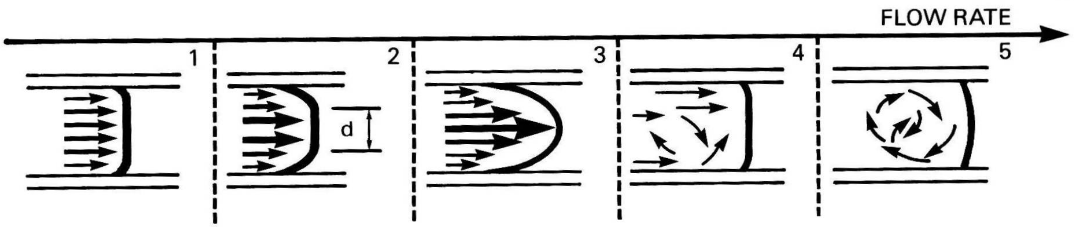

Figure 9 Transfer from laminar 1 to turbulent flow 5. (Source: Schlumberger D., Cementing Technology, Nova Communications Ltd, London 1984)

The table below shows one calculation of the pressure drop calculation with adjusted flow of 20m³/h. Density was estimated according to mineralisation of water which correlates to the value 1,1kg/l. Viscosity was also assumed to standard values in this stratygraphy.

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[11] Wikipedia internet source

				Pipe flow			Annular flow	
Borewhole depth	L			1937	m			
ID tubing (2 5/8“)	D	66.7	mm	0.0667	m			
OD tubing (2 7/8“)	D1	73	mm	0.073	m			
ID casing (6 5/8“)	D2	168.3	mm	0.1397	m			
Density	ro	1.1	kg/l	1100	kg/m3			
viscosity	mi	0.325	cP=mPa.s	0.000325	Pa.s			
Flow	Q	20	m3/h	0.005556	m3/s			
Average velocity	v			1.589959	m/s		0.498844	m/s
Reynolds number	Nre			358939	Turbulent		91951	Turbulent
Fanning friction factor	f			0.004414			0.005796	
Frictional pressure drop	Pf			712966.3	Pa		30834.7	Pa
	Pf			0.713	MPa		0.031	Mpa
Total pressure drop	Pipe & Annular flow					**0.744**	MPa	

Table 7 Summary of equations for Newtonian Fluids (Coherent unit system), Source: Schlumberger D., Cementing Technology, Nova Communications Ltd, London 1984

For the calculation of the circulation pump power output, there was an online software used called the Grundfos WebCAPS 2009.02.69. This software is based on the products for Grundfos pumps which are standardized for any application. The application was set up for sizing the circulation pump for Groundwater supply. Then the borehole installation with closed tank was applied. The input data were the flow, head (which was converted from the pressure drop) with no other limits. As a result, different flow has various circulation pump units in kW.

	Flow [m3/h]	Pressure drop [Mpa]	Head [m]	Circ. pump Pwr ouput [kW] *
Velke Kapusany 8	3	0.049	4.9	NA
	5	0.123	12.3	0.75
	8	0.286	28.6	1.1
	20	1.488	148.8	15
Secovce 5	3	0.027	2.7	NA
	5	0.068	6.8	NA
	8	0.159	15.9	0.75
	20	0.826	82.6	9.2

Table 8 Power output of circulation pumps for different flows

Due to huge gap between the 8 to 20 m³/h range flow and small differences among the 3-5-8 m³/h, there was decision made to change the range for 10, 15,.. 40 m³/h flow (2,8 to 11,1 kg/s). The figure below shows steeper curve of the circulation pump output with the flow 25 m³/h and higher. Thus above the value, the circulation pump requires more energy with less flow pressure.

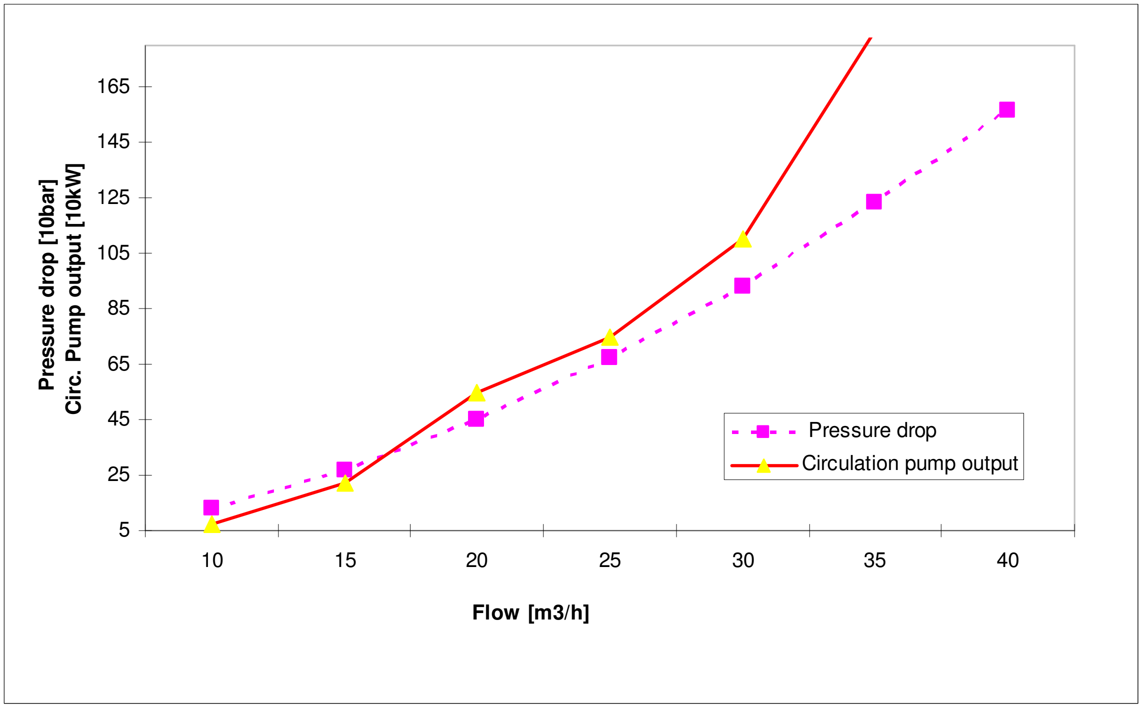

Figure 10 Dependency of circulation pump output with pressure drop for Secovce

8.2 Simulations with different pipe diameters

To find the most optimal pipe diameter, there were three simulations proposed. The casing is fixed to actual situation on site.The only available changes could be done with the tubes, specifically in the gap between the casing and outer diameter of a tube, the gap between the outer tube and inner tube as insulation layer and the inner tube in itself.

Simulation 1	Diameter	**Simulation 2**	Diameter	**Simulation 3**	Diameter
Casing D2	6 5/8	Casing D2	6 5/8	Casing D2	6 5/8
OD tubing D1	4	OD tubing D1	4 1/2	OD tubing D1	4 1/2
ID tubing D	3	ID tubing D	3 1/2	ID tubing D	3
Ratio OUT/IN	1: 3	Ratio OUT/IN	1: 2	Ratio OUT/IN	1: 2.6

Table 9 Overview of 3 different pipe diameters (in inches)

The ratio value on the bottom of the table indicates the ratio between the area of the gap, where the liquid is flowing in (between the casing and outer tubing) and the area of the tube, where the heated liquid is flowing out.

The Simulation 1 has the largest area for liquid flowing in, the Simulatin 2 has the largest tube for the liquid flowing out and the Simulation 3 has the largest insulation layer. Each situation will indicate different behaviour of the pressure as well as the temperature of the liquid.

8.3 Thermal flux calculations

Heat flux or thermal flux, sometimes also referred to as heat flux density or heat flow rate intensity is a flow of energy per unit of area per unit of time. In SI units, it is measured in [W·m-2]. It has both a direction and a magnitude so it is a vectorial quantity. To define the heat flux at a certain point in space, one takes the limiting case where the size of the surface becomes infinitesimally small[12].

Heat flux is often denoted Φ, the subscript q specifying heat flux, as opposed to mass or momentum flux. The most important appearance of heat flux in physics is in Fourier's law describing heat conduction.

For the purpose of heat flux calculation, there was an Excel calculation with macros used, which was developed by OMV.

Input data consist of more parameters influencing the result value of the temperatures. Tinlet is the temperature of the fluid reinjected back to the well and Tamb is the temperature of the exterior. Specific heat capacity was for our purpose 3930 J/kg/K with density of 1012 kg/m³. Further input data like the well depth, diameters of pipes and

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[12] Wikipedia

casing, temperature of the fluid remains the same. The la is the length in metres, calculated from total depth of a well divided by 400 nodes. The temperature Twai is the temperature of outer surface of the outer tube, Twao is the temperature of the inner surface of the same tube, Twio is the temperature of the outer surface of inner tube and Twii is the temperature of the inner surface of the inner tube. Twii is a relevant temperature of the heated fluid flowing up to the surface.

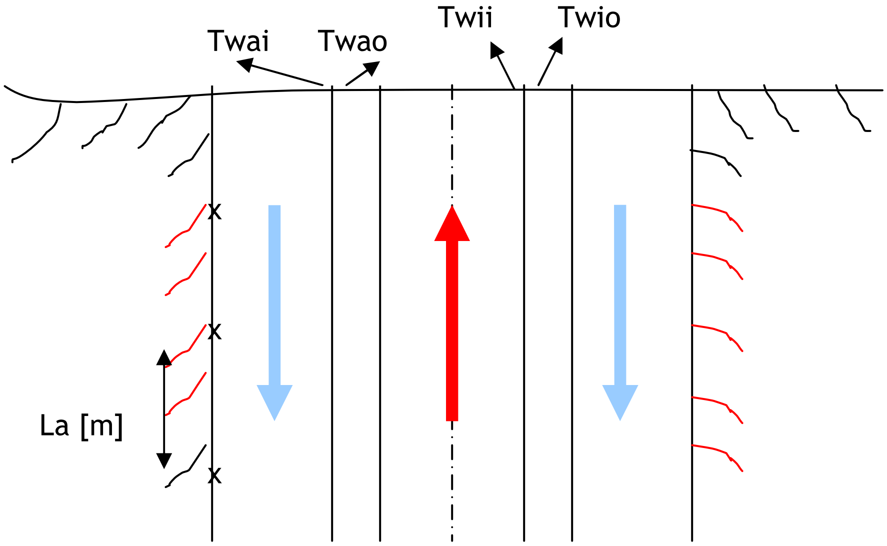

Figure 11 Schematic drawing of different measurement points for heat flux calculation

The output of this calculation is thus the Twii, which gives the information, how was the working fluid heated up during the flow down from the heated surface of casing.

The Excel programme calculates the Q, the output thermal capacity of the borehole. It was calculated as

$$Q\ [Wth] = Twii\ [C] \times Mass\ flow\ [kg/s] \times Heat\ capacity\ [J/kg/K]$$

Firstly, the calculation was done for three simulations for seven different mass flow speeds (10, 15,..40 m³/h) of the Secovce well.

Simulation 1

Flow [m3/h]	Flow [kg/s]	Pressure drop [Mpa]	Pressure drop [10kPa]	Circ. pump Pwr ouput [kW] *	Circ. pump ouput [10kW]	Twii [C]	Q [kW]	Q-C.pump output
10	2.778	0.129	12.9	0.75	7.5	51.55	257	250
15	4.167	0.268	26.8	2.2	22	44.831	276	254
20	5.556	0.45	45	5.5	55	41.052	285	230
25	6.944	0.672	67.2	7.5	75	38.648	291	216
30	8.333	0.933	93.3	11	110	36.987	294	184
35	9.722	1.232	123.2	18.5	185	35.773	297	112
40	11.111	1.566	156.6	26	260	34.847	299	39

Simulation 2

Flow [m3/h]	Flow [kg/s]	Pressure drop [Mpa]	Pressure drop [10kPa]	Circ. pump Pwr ouput [kW] *	Circ. pump ouput [10kW]	Twii [C]	Q [kW]	Q-C.pump output
10	2.778	0.088	8.8	0.55	5.5	51.598	258	252
15	4.167	0.183	18.3	1.5	15	44.857	276	**261**
20	5.556	0.307	30.7	3	30	41.059	285	255
25	6.944	0.459	45.9	5.5	55	38.652	291	236
30	8.333	0.637	63.7	9.2	92	36.989	294	202
35	9.722	0.841	84.1	13	130	35.774	297	167
40	11.111	1.069	106.9	18.5	185	34.848	299	114

Simulation 3

Flow [m3/h]	Flow [kg/s]	Pressure drop [Mpa]	Pressure drop [10kPa]	Circ. pump Pwr ouput [kW] *	Circ. pump ouput [10kW]	Twii [C]	Q [kW]	Q-C.pump output
10	2.778	0.145	14.5	0.75	7.5	51.304	254	247
15	4.167	0.3	30	2.2	22	44.745	274	252
20	5.556	0.504	50.4	5.5	55	41.013	284	229
25	6.944	0.753	75.3	9.2	92	38.628	290	198
30	8.333	1.045	104.5	13	130	36.975	294	164
35	9.722	1.38	138	22	220	35.765	297	77
40	11.111	1.754	175.4	30	300	34.841	299	-1

Table 10 Thermal flux of the three simulations

For proper diversification of all the simulations, the pressure drop as well as circulation pump output was multiplied with different scales.

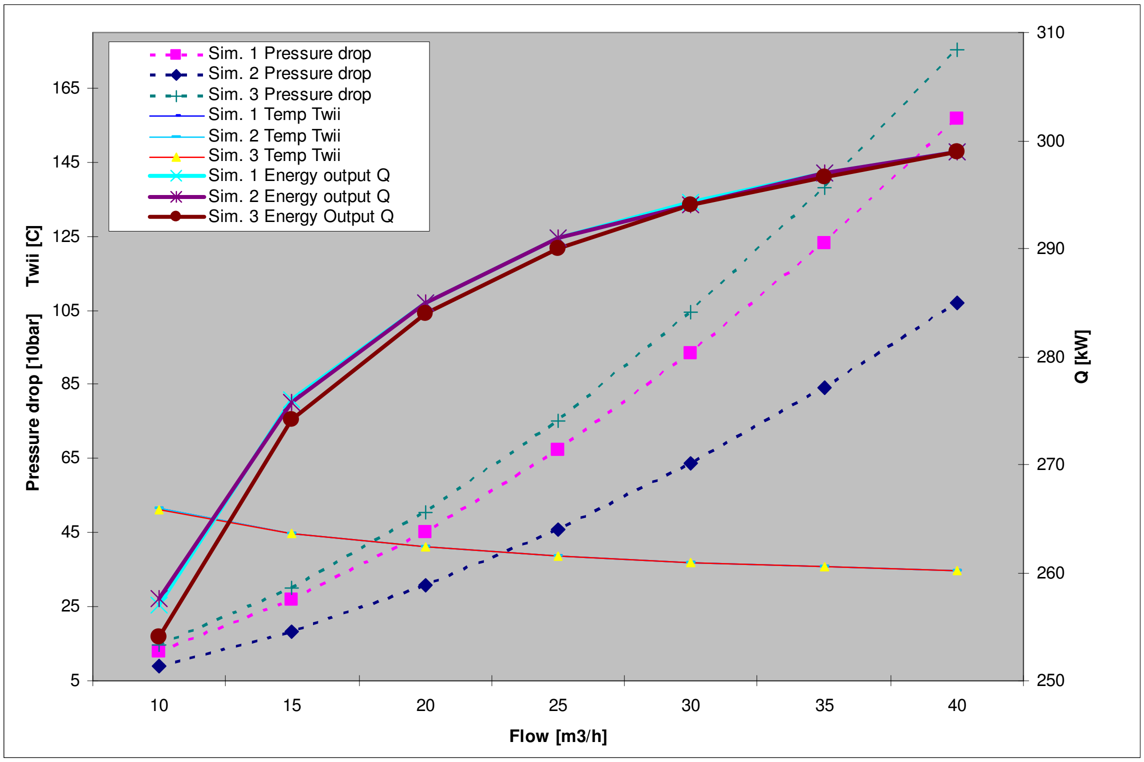

Figure 12 Flow simulation of tested output temperature Twii, energy output Q and pressure drop with different flow speed

As the figure above indicates, the pressure drop for the working flow is highest for the Simulation 3, due to widest insulation layer of the tubes. In contrary, the Simulation 2 has the lowest pressure drop due to largest diameter of inner pipe. The temperatures Twii are for all the simulations very similar.

The Simulation 1 shows the highest energy output performance Q. Slightly lower performance Q indicates the Simulation 2. The worst scenario is for the Simulation 3 which has evidently lower energy output. This character of the performance curve is a result of too wide insulation layer which is inefficient for the velocity of the liquid. In addition, the insulation layer reduces the volume of the working fluid circulating through the system.

The best ratio between the output energy performance and input energy for the circulation pump shows the last column in the tables above. In fact, the energy output Q is reduced by the output capacity of the circulation pump. It should be noted that the values are not comparable, due to electric kWe of the circulation pump and thermal energy output in kWth. On the other hand, it shows the largest difference between the output and input of energies.

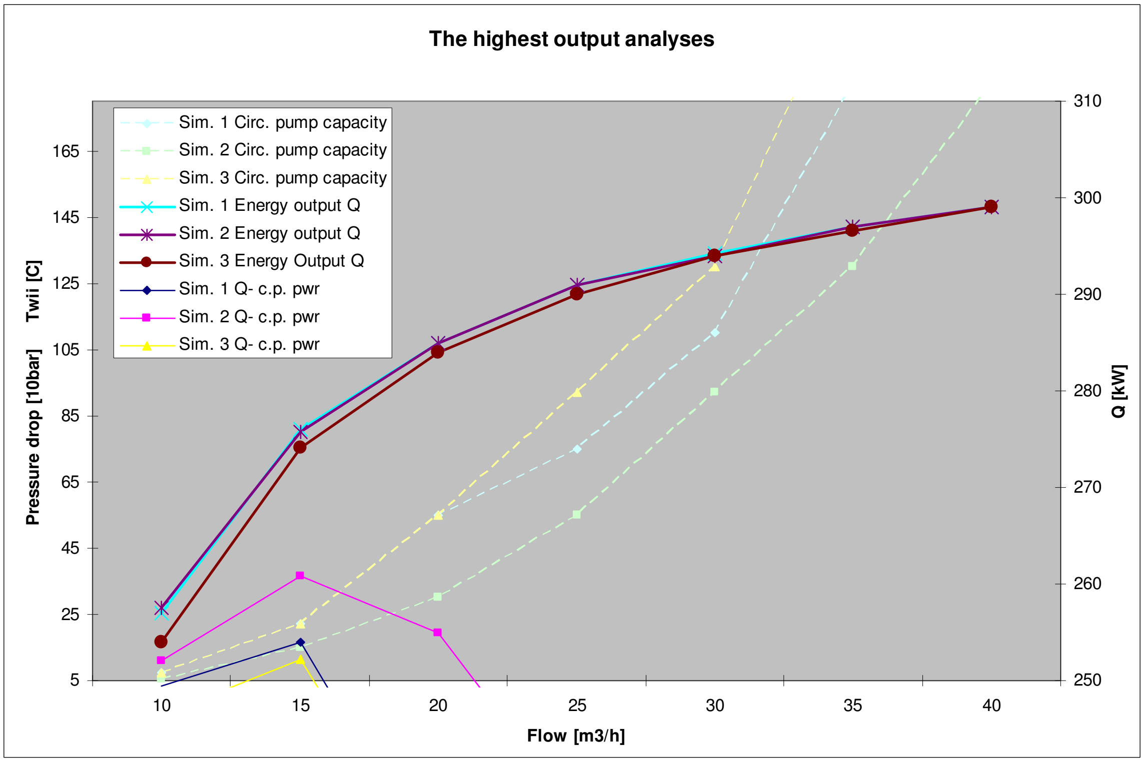

Figure 13 The best ratio between the output energy performance and input energy for the circulation pump

The best value is for the Simulation 2 with the fluid velocity of 15 m³/h (4,17 kg/s) with the energy output of 276 kWth.

8.4 Calculation of the second borehole heat exchanger

The other well Velke Kapusany has better condition for geothermal purposes. It has 145 C with the depth of 3490m. Due to the best values of the Simulation 2 (casing 6 5/8, internal tubing D= 3 ½, outer tubing D1= 4 ½) of the previous borehole, there was only this case calculated.

Simulation 2

Flow [m3/h]	Flow [kg/s]	Pressure drop [Mpa]	Pressure drop [10kPa]	Circ. pump Pwr ouput [kW] *	Circ. pump ouput [10kW]	Twii [C]	Q [kW]	Q-C.pump output [kW]
10	2.778	0.159	15.9	1.1	11	75.481	518	507
15	4.167	0.33	33	2.2	22	64.163	592	570
20	5.556	0.553	55.3	5.5	55	56.952	**632**	**577**
25	6.944	0.827	82.7	9.2	92	52.063	657	565
30	8.333	1.148	114.8	15	150	48.560	673	523
35	9.722	1.515	151.5	26	260	45.935	685	425
40	11.111	1.927	192.7	37	370	43.899	694	324

Table 11 Thermal flux table for the second well

As shown in the table above, the best energy output from the well in respect of the energy necessary for circulating the working fluid, is with the flow of 20m^3/h with the total output of 632kWth.

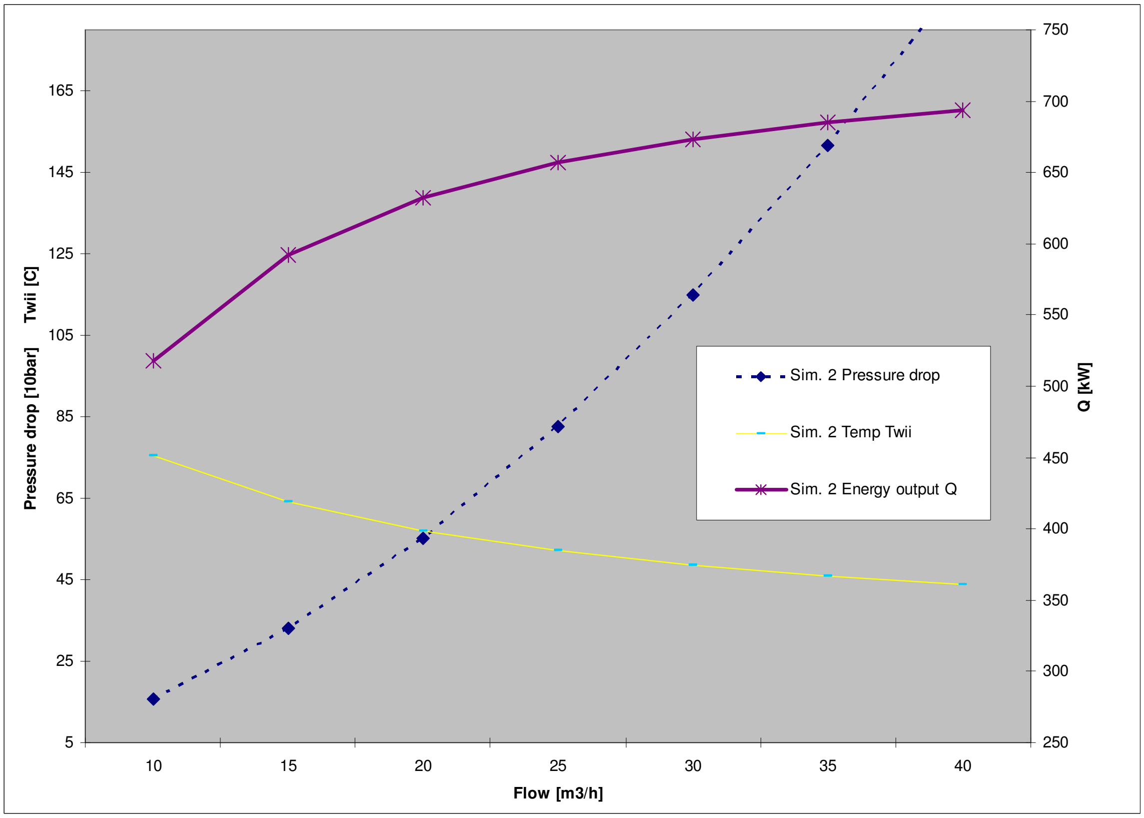

Figure 14 Flow simulation of the second well

9 Thermal efficiency for electricity of the borehole heat exchanger

In thermodynamics, the thermal efficiency is a dimensionless performance measure of a thermal device such as an internal combustion engine, a boiler, or a furnace, for example. The input to the device is heat from the rock underground. The desired output is mechanical work, or heat or possibly both. This case study is focused solely for mechanical work transferred to electricity. Because the input heat normally has a real financial cost, a memorable, generic definition of thermal efficiency is

$$Thermal\_Efficiency = \frac{Net\_work\_output}{Total\_heat\_input}$$

which is between the range 0 and 1. Some heat engines perform better than others that mean they convert more of the heat they receive to work. In fact, the most efficient heat engines reject almost one- half of the energy they receive as waste heat. For affordable technology used today, the values of efficiency vary between 20 and 30%.

This means for the best value of previous calculation, which is 632kWth, a range between 126 and 190kWe. In addition, it is necessary to reduce the power output for the pump (5.5kW).

For comparrison the values of the final power output, temperature of the reservoir and the flow of the working fluid, the figure below correlates with the calculated values.

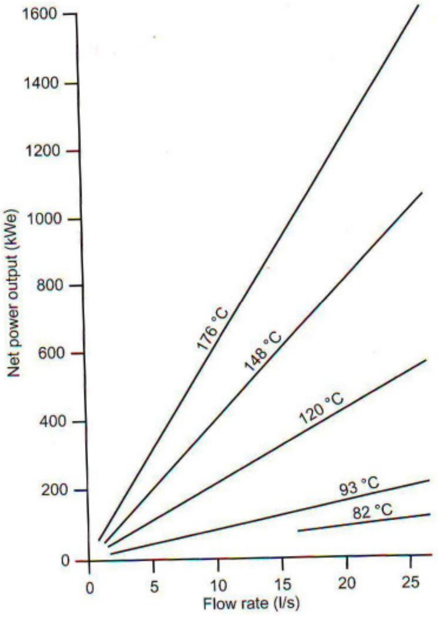

Figure 15 Net power output for low-enthalpy geothermal fluids (Source: Lund and Boynd 1999)

The flow rate which was the most optimal calculated in the previous chapter is 20m^3/h (5.56kg/s). If the line with the temperature of 148 C is considered (closest to 145 C), the Net power output is then around 200kWe. Concludingly, this value correspondent with the estimation of the power output after the thermal efficiency reduction (20- 30%).

10 Stored heat calculation of two intenferenced wells

In this chapter, calculation of the stored heat in the reservoir between two boreholes Kapusianske Klacany 28 and 29 is described. The result of this calculation results in power potential of the heat in the mass in two phases, from initial to final state of the reservoir. Initial stored heat is actual heat measured on site. The final state of reservoir is then assumed to be when the cold water has completely "swept" the heat out of the reservoir. The initial temperature is T= 110 C, final temperature is To= 80 C.

The geothermal reservoir between the wells Kapusianske Klacany 28, 29 was estimated according to similarities of the porosities of local wells. There are three wells with similar porosity in the range of 11- 17%. The depth range with this porosity for all the wells near by those 28 and 29 is 1360m to 2100m (740m thickness). The horizontal dimensions of the reservoir are estimated according to distance between the well 28 and 29 (500m) and local wells with similar values in the area of 1000m. Total volume of the reservoir is overlapping certain distance. As a result, the dimensions were estimated for 1000m x 1000m x 800m, which is 0.80km^3.

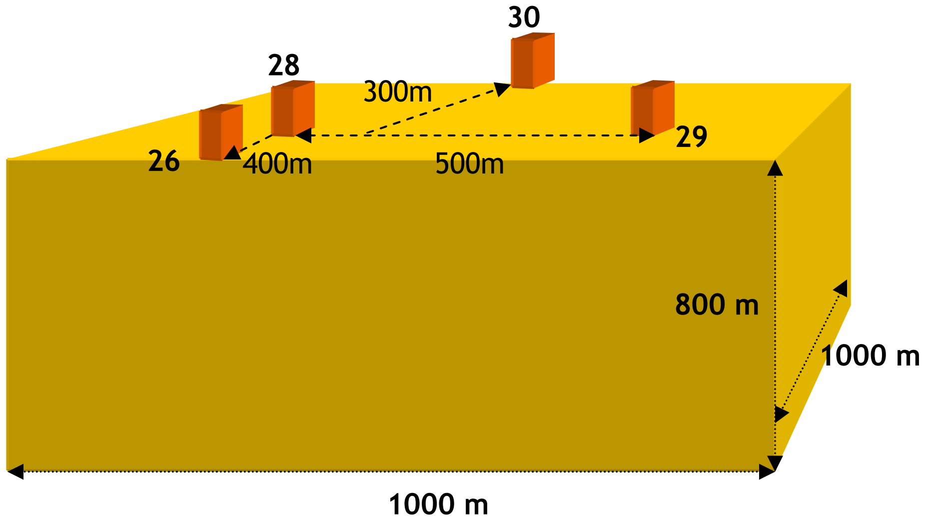

Figure 16 The Geothermal reservoir volume

Porosity Φ is defined as the ratio of volume of pore space (i.e. the volume that can be occupied by the fluid) to the total volume of the system. Porosities are of the order 5-30% in the production zone of a geothermal reservoir. In the tighter surrounding rock porosity may be 1% or lower, in more open area like sand around 30%. For the well Kapusianske Klacany 28, there has been 9 analyses done on site with average value of porosity Φ= 11.4% in the depth range of 1360- 2160m. The well Kapusianske Klacany 29 had 14 analyses with value of Φ= 17.6%. The average porosity is thus Φ= 14.5%.

A saturated liquid contains as much thermal energy as it can without boiling (or conversely a saturated vapor contains as little thermal energy as it can without condensing).

A saturated vapour is a vapour whose temperature and pressure are such that any compression of its volume at constant temperature causes it to condense to liquid at a rate sufficient to maintain a constant pressure[13].

Thus saturations are the volume fractions of liquid S_l and vapour S_v and are commonly used in reservoir engineering to measure the proportion of water and steam (gas). It is important to note that,

$$S_l + S_v = 1$$

which means that the variables are dependent. The local values from the well were not calculated from the 28 and 29, due to lack of lodging analyses. Therefore the nearest well with lodging charts was accepted. The average value S_l is 65%, so for the fraction of vapour and natural gases S_v is 35%.

Density of rock were also measured from the lodging charts of the local wells (2513, 2396, 2381, 2364kg/m³) resulting with average value of ρ=2413 kg/m³. Specific heat of rock we assumed to typical value of c_r=1000J/kg.K for clayed sand with porosity mentioned above.

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[13] Wikipedia

There is no single process that describes the flow through reservoir. The flow can be a flow of hot water into a cold part of the reservoir, so that heat is lost and the enthalpy of the flow decreases. The flow could be also isothermal, if it has been flowing for a long time so that the rocks are fully heated. The calculation assumes the stored heat in the reservoir relative to a final condition of saturated liquid of To= 80 C which is the lowest possible working temperature.

The Temperature and the Pressure of the saturated steam are mutually dependent. When one of them is given, the other is determined. In this case, there were the temperatures and the pressure was determined in the Saturated Steam tables. Also, further properties of saturated steam were determined from the table.

Temperature	**T**	**110**	**To= 80**	**C**
Absolute Pressure	P	1.4338	0.4741	bar
Enthalpy				
Saturated Liquid	hf	461.42	335.01	kJ/kg
Saturated Vapor	hg	2691.1	2643	kJ/kg
Density				
Saturated Liquid	ρl	950.95	971.77	kg/m3
Saturated Vapor	ρv	0.82692	0.29367	kg/m4

Table 12 Property of saturated steam table for 110 and 80 C

In further calculation, there is a value of triple point of water which is 0.01 C in the steam table. In thermodynamics, the triple point of a substance is the temperature and pressure at which three phases (for example, gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium[14].

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[14] International Union of Pure and Applied Chemistry (1994)

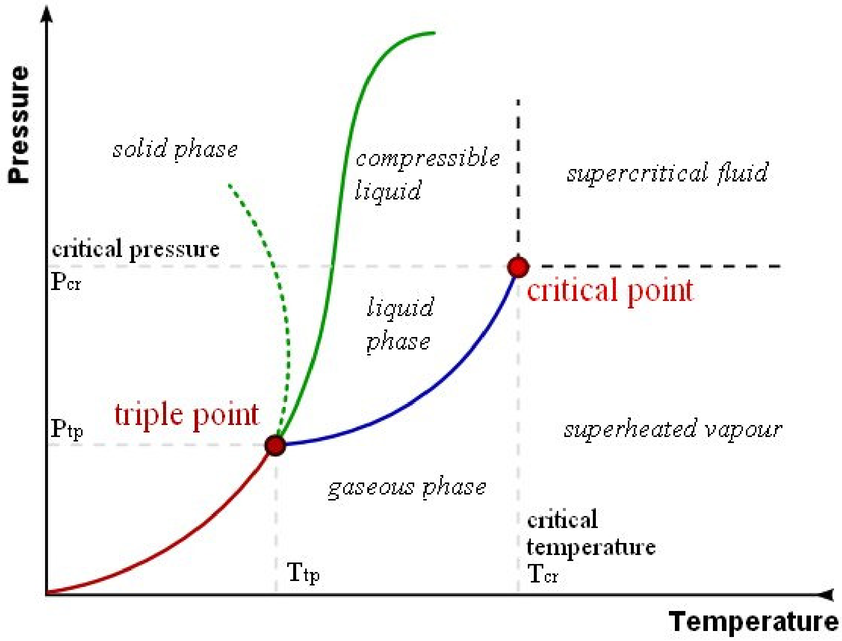


Figure 17 Triple point of water

If a fluid is moving the power put in by the Force x Velocity produced by pressure adds to the energy,

$$Energy = Thermal\_Energy + Power$$

or

$$Energy = \rho.u.V + p.V = \rho.\left(u + \frac{p}{\rho}\right).V$$

where ρ is a density of rock, V is a volume of reservoir, p is a pressure and u is specific energy of water. This is calculated from the formula,

$$h = u + \frac{p}{\rho}$$

Thus the specific energy u must be modified to an enthalpy h which is defined in previous table. This is the concrete formula for calculating specific energy for water

$$u_l = h_f - \frac{P}{\rho_f}$$

Similarly, the specific energy of steam is calculated for actual and final temperatures.

Definition	symbol	110 C	80 C	unit
Specific energy for water	ul	461.3	335.0	kJ/kg
Specific energy for steam	uv	2517.7	2481.6	kJ/kg

Table 13 Steam and water characteristics

The energy content of water and steam is divided into the initial and final energy for rock and fluid. Initial energy in rock is thus,

$$Initial\_Energy_{rock} = (1-\phi).\rho_r.c_r.(T - T_{triple}) \quad \text{Equation 1}$$

where ρ_r is density of rock (2413 kg/m³), c_r is specific heat of rock, T is initial and Ttriple is triple point of water. The initial energy in fluid is,

$$Initial\_Energy_{fluid} = \phi.(\rho_l.u_l.S_l + \rho_v.u_v.S_v) \quad \text{Equation 2}$$

where ρ_l , ρ_v is from the Saturated steam table. Total Initial Energy in rock and fluid is,

$$Total\_Initial\_Energy = (Initial\_Energy_{rock} + Initial\_Energy_{fluid}).V \quad \text{Equation 3}$$

with V as a volume of the reservoir. In addition, the reservoir could be divided into a number of sub-regions with volumes V_1, V_2,..V_n each of which is in a approximately uniform thermodynamic state. The initial stored heat is then given by

$$H_i = \sum_{j=1}^{N} A_{ej}^{i}.V_j \, . \quad \text{Equation 4}$$

The Final Energy in rock for the temperature To is calculated as Equation 1, just T is equal to To= 80 C. Similarly, the Final Energy in fluid is calculated based on the Equation 2.

Energy content of water and steam	**Initial** $H_{initial}$	**Final** H_{final}	Unit
Energy in rock	226.9	165.0	MJ/m3
Energy in fluid	41.4	30.7	MJ/m3
Energy	268.4	195.7	MJ/m3
Total Energy= V.Energy	**2.14696E+11**	**1.56596E+11**	**MJ**

Table 14 Initial and Final Energy content of water and steam

It is interesting to note, that over 80% of the energy in the geothermal reservoir is in the rock.

The theoretical maximum quantity of useful heat Hth, which is available for exploitation, is given by

$$H_{th} = H_{initial} - H_{final}$$

In this case, the Hth is 58100 TJ. The actual or design quantity of useful heat Hde is obtained by multyplying Hth by a recovery factor Rf

$$H_{de} = R_f . H_{th}$$

The Rf value is not very well known. Values in the range 0.1- 0.5 have been suggested by various authors but no really convincing reasons have been given for the choice. Some workers suggested that the calculation of the final energy should not be based on a final state the reservoir containing cold water, because the reservoir will cease useful production when the final temperature is at some higher value, about 180 C for electricity production.

For this case, there is an assumption of Rf= 0.25. Then the Hde is 14525 TJ. The Power potential in MWe is calculated as

$$W_e = \frac{H_{de} . \eta_c}{10^6 . L_f . P_L}$$

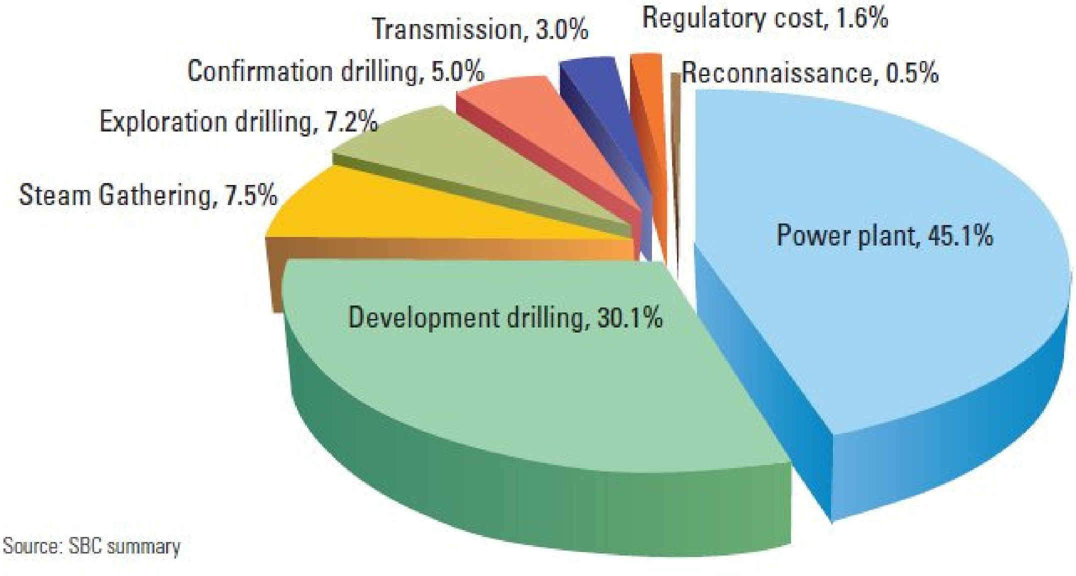
where η_c is conversion efficiency (0.1- 0.2), L_f is power plant load factor or capacity factor (0.9- 0.95) and P_L is power plant life converted into seconds. Due to higher proportion of water in the reservoir (compare to steam), the conversion efficiency with 0.1 was chosen. The average value of 0.92 was chosen for capacity factor. The power plant life is expected to be for 20 years. As a result, the final power potential of the reservoir is 2.5 MWe.

11 Economics of small power plants using existing resources from depleted oil and gas fields

The selection of existing hydrocarbon boreholes faces more advantages. All are finally reducing the risk of uncertainty during the geothermal exploitation. This is a significant contribution for decision-makers in any investment.

The first major advantage is the understanding of geological conditions beneath the soil. There have been analyses done when drilling was applied as well as during the gas or oil exploitation. Moreover, mineralization, gas interferences, porosity, temperature, pH of working liquid, chemical analyses of the rock, viscosity and other properties of a well which are observed on site. However, the main reason for original drilling was due to hydrocarbon. Therefore analyses have been done just for its purpose. If there was a high level of water in the hydrocarbon reservoir, Nafta,a.s. released from the production.

The other huge advantage is to use existing boreholes for geothermal purposes. If the borehole is in a feasible condition, it can be used for production. Moreover, borehole diameter, the existing quality of casing (corrosion, depreciation) is crucial factor for a new production. The costs of drilling cover 30% of the total cost of geothermal power plant.



Source: SBC summary

Figure 18 Geothermal power plant costs break-down (Source: Schlumberger Consulting)

Minimizing the development drilling cost would reduce the initial investment costs. The project is then more feasible for bank financing, reducing huge risk during the drilling and exploration.

11.1 Economical analyses of the borehole heat exchanger

The capacity of the power plant calculated in this case is maximum 200kWe. Such a small installation has rather higher capital cost per kW, then lower cost in a huge installation over 10MWe. On the other hand, there are specific advantages that should be considered:

1. The plants are very transportable. For 100 to 300kWe, the entire plant including the cooling tower can be built on a single skid that fits in a standard trans-ocean container.
2. Binary power plants can accommodate a wide range of geothermal reservoir temperature (100 to 150 C). Above 150 C, flashed steam plants usually prove less expensive than binary plants.
3. Power plant designs emphasize a high-degree of computer-based automation. There is no skilled personnel necessary.
4. The system releases no green house gases to the atmosphere.
5. All wells could be drilled by truck-mounted rigs.
6. Injection well and field piping costs relatively low.

The economical analyses for the borehole heat exchanger use standard cash flow calculation with the basic result as IRR, NPV or Pay back period. The table below was filled in according to the values of previous calculations in the chapter 8.4.

Depth of the well	m	3490
Geothermal gradient	K/m	0.041547
Reservoir temperature	℃	145.00
Flow of the well	l/s	5.556
Well head temperature	℃	140
Reinjection temperature	℃	60
Conversion efficiency thermal power	%	96
Full load hours per year	h	7920
Thermal Power	MWth	2
Thermal Energy	GWh	14
Electricity per year	GWh	1.6
Received price per MWh electricity sold	€	195.84
Size of electric power station	MWe	0.2
Total Investment	mn €	0.9
Conversion efficiency electric power	%	11
Price increase for electricity bought	%p.a.	0
Price increase general costs	%p.a.	3
Price of CO_2 Emission Reduction Certificates (ERUs) sold	€	0
Capacity of 1 W =	kcal/h	1.162222

Table 15 Base assumption for the 200kWe installation

The CAPEX and OPEX table was formed according to assumptions of more sources, one from particular example of 300kWe developed by Entingh, Easwaran and McLarty (1994)[15] and other one from the *Low-enthalpy geothermal resources for power plant*[16] book. The received price per MWh electricity sold, another words feed-in tarrif was based according to Slovak Regulatory Office (URSO) for the year 2010 (Vynos 7/2009). Full load hours were spread for 330 days per year, which should be base load electricity plant.

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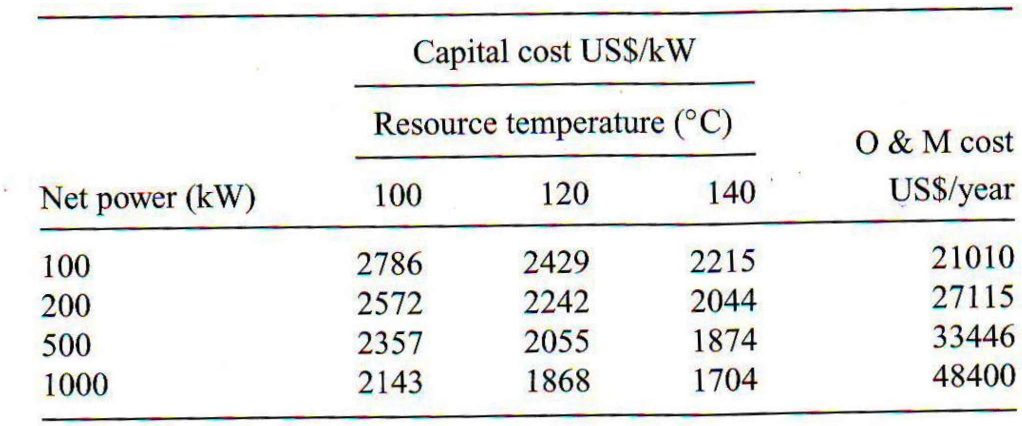
[15] GHC Bulletin, June 1999, Small geothermal power project examples, John W. Lund, p. 11

[16] D. Chandrasekharam & J. Bundschuh, Low-Enthalpy Geothermal Resources for Power Generation, 2008 CRC Press, p.112



	Capital cost US$/kW			
	Resource temperature (°C)			O & M cost
Net power (kW)	100	120	140	US$/year
100	2786	2429	2215	21010
200	2572	2242	2044	27115
500	2357	2055	1874	33446
1000	2143	1868	1704	48400

Figure 19 Unit cost of electricity generated from low-enthalpy based small power plants (Source: DePippo 1999)

Parameter	Depreciation term (year)	Mio EUR
Repairing of existing hydrocarbon well	30	0.10
Drilling reserve	30	0.05
Building & land	15	0.10
Pump	5	0.05
Electric power station	20	0.50
Other		0.05
Total CAPEX € million		**0.85**

Table 16 CAPEX table for 200kWe plant (in Mio EUR)

This assumption does not calculate with drilling cost, but just reparation of existing gas well. In this situation, the CAPEX per kW is 4250 EUR/kW which is rather conservative value compare with the Figure 19.

Parameter	1000 EUR
Increase in provisions	20
Material and third party costs	5
thereof electric power	20
Personnel costs	0.5
Other operating expenses	2
Start up costs	5
Maintenance	0.02
Total OPEX T€	**52.5**

Table 17 OPEX table for 200kW plant (in 1000 EUR)

Similarly, the OPEX was estimated by the same examles. As a result, the Operation and Maintenance costs is 52 500 EUR per annum.

The cash flow calculation with equity financing of interest rate of income and expenses (4.5%) and timetable scenario for 20 years is shown in the following figure.

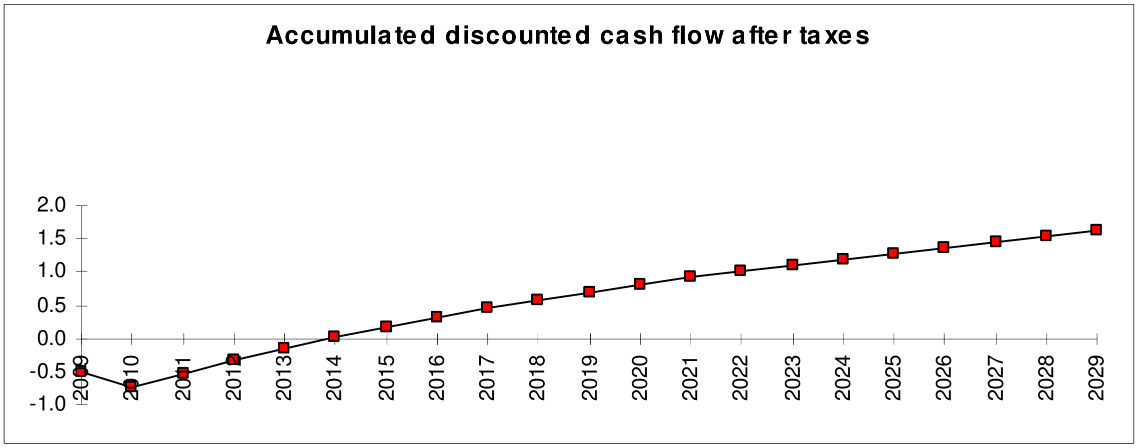


Figure 20 Cash flow after taxes for 200kWe power plant

The final table shows interesting values, which are worth to consider.

Internal rate of return (IRR)	25.5%
Net present value (NPV)	1.6
Pay back period	4.9

Concludingly, the project is valuable with very short payback period of the equity.

11.2 Economical analysis of the geothermal reservoir

This analysis is for the 2 boreholes, one for production and the other one for reinjection of working fluid. The boreholes are existing, previously used for gas exploration. The details of calculations of geothermal reservoir (2.5 MWe) are described in the chapter 10.

The calculation has estimations based on assumptions from the the same examples. The analysis did not calculate with selling the heat to the municipality, but it was focused just for the electricity purchase.

Depth of the well	m	2100
Geothermal gradient	K/m	0.0523
Reservoir temperature	°C	109.83
Flow of the well	l/s	100
Well head temperature	°C	107
Reinjection temperature	°C	46
Conversion efficiency thermal power	%	96
Full load hours per year	h	7920
Thermal Power	MWth	24
Thermal Energy	GWh	194
Heating hours per year	h	3200
Electricity per year	GWh	21.3
Received price per MWh electricity sold	€	195.84
Size of electric power station	MWe	2.5
Total Investment	mn €	23.7
Conversion efficiency electric power	%	11
Price increase for electricity bought	%p.a.	0
Price increase general costs	%p.a.	3
Price of CO_2 Emission Reduction Certificates (ERUs) sold	€	0
Capacity of 1 W =	kcal/h	1.162222

Table 18 Base assumption for the 2.5 MWe installation

The flow of the well was estimated according to final size of electric power station and the size of casing, which is 6 5/8 of inches. It should be noted, that the flow is rather for hydrogeothermal well, as for hot dry rock. Due to short distance between the production and reinjection wells and high porosity, the flow is acceptable.

The other values are the same from previous chapter.

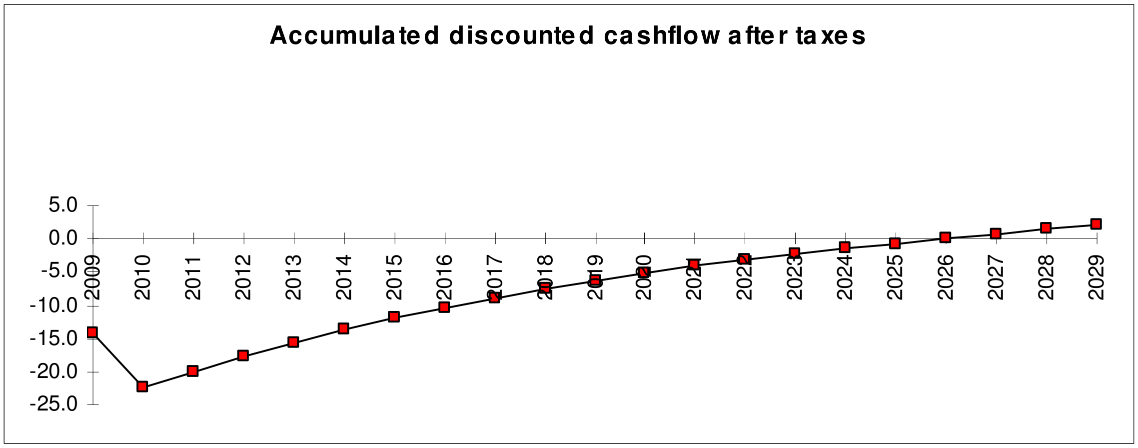
Parameter	Depreciation term (year)	Mio EUR
Repairing of existing hydrocarbon well	30	10.0
Drilling reserve	30	1.0
Building & land	15	1.0
Pump	5	1.6
Heating redundancy	5	0.0
Heating pipeline	30	0.0
Electric power station	20	9.0
Other		1.1
Total CAPEX € million		**23.7**

Table 19 CAPEX table for 2.5 MWe plant (in Mio EUR)

This assumption does not calculate with drilling cost, but just reparation of existing gas wells. In this situation, the CAPEX per kW is 9480 EUR/kW.

Parameter	1000 EUR
Increase in provisions	48
Material and third party costs	500
thereof electric power	1000
Personnel costs	50
Other operating expenses	200
Start up costs	500
Maintenance	2.0
Total OPEX T€	**2300.0**

The total OPEX is 2.3 Mio EUR based on annual basis. Due to high automation of the plant, there was no necessity for numerous working hours and skilled personnel.



The payback period for this case is almost 17 years.

Internal rate of return (ROR)	7.1%
Net present value (NPV)	1.9
Pay back period	16.9

This project is less profitable than the previous one, but it indicates some profit.

12 Conclusion

As the economics shows, both the projects are feasible for realization. In fact, the values of the projects can vary because there are always factors that change the plans. It is important to note, that the results of the energy potential were calculated also with assumptions which could not meet the real facts when it comes to realization. Therefore higher risk of these projects should be accepted, compare to other renewable energy sources. This might reduce the willingness of some investors to develop so risky projects with uncertainties which are not equal to the economic benefits. Indeed, unpredicted volume of the heat storage, highly aggresive chemical constituents in geothermal waters, flamable and toxic gases and many other items are potenitally influencing the budget and could increse the initial investment costs.

On the other hand, there is some information, based on measurements from hydrocarbon exploitation that are done from real tests. It is temperature, mineralisation and basic chemical analyses of the fluid, simple flow test, interference among the boreholes which gives indicative conception of the energy potential. The importance of these concrete numbers is higher as the assumptions based on theory. Therefore those values are the first step for evaluation of the profitability of the projects.

For overall and deeper view for the project, it is necessary to do further measurements and test exploitation. During the hydrocarbon exploration, all the chemical analyses were done for original purposes- gas or oil drilling. If new purpose of the utilization of borehole is decided, it is necessary to do new analyses for geothermal purposes. All the geothermal waters reside in the reservoir for sufficiently long and have achieved chemical equilibrium with the reservoir rock. Thanks to further chemical analyses of geothermal waters, the reservoir characteristics are more understandable and provide critical information during new exploration.

The detailed long-term flow test in a small application will also come up with new results determining technology which fit to these conditions. Broad scope for testing of the borehole is crucial for next decisions. The more is invested during the measuring period, the lower is the risk of unpredicted costs in realization.

Comparing the results of the last chapter, small applications with 200- 500 kW of power unit from heat exchanger are more adaptable for existing hydrocarbon boreholes as the large ones utilizing boreholes for production and re-injection. This is due to small diameters of the boreholes that are suitable more for oil exploitation. Geothermal working fluid requires higher capacity. Therefore new boreholes for geothermal purposes have normally double the diameter of hydrocarbon borehole. In addition, more efficient circulation pump is needed which consumes more electricity. Also, the velocity of circulation is limited by the efficiency of heat transfer. System optimalization is the best option how to find the highest performance ratio.

It is clear that the viability of the projects depends on the existing situation of a well. Further development in testing methods and analyzes of existing status of hydrocarbon boreholes brings more light from assumtions to real values. The risk of having very different assumptions used in the calculations with real values is reduced if measurements are done with specific purposes. Testing is still more economical than drilling new borehole. New innovative technology that measures all the crucial information that was not explored during the hydrocarbon analyzes is also a solution for better understanding what is under the ground.

Geothermal yields from depleted oil and gas fields in Slovakia are already feasible. The best selected boreholes have already positive profitability. If more detailed tests and analyzes is done in a borehole, the risk is mitigated to minimum. The system optimalization and new improvements can increase the harvest from well additionally. Then the unused hydrocarbon fields are coming back to its operation, but in a different more sustainable way.

References

Bertani Ruggero, Ingvar B. Fridleifsson , John W. Lund; „The possible role and contribution of geothermal energy to the mitigation of climate change“; IPCC Geothermal 11 February 2008.

Bertani Ruggero, “Geothermal Energy: An overview on resources and potential”, 2008.

Centre for Scientific Tourism, “Geology and Geomorfology”, http://www.ecosystems.sk/pages/geo.html, 2009.

Chandrasekharam D. & J. Bundschuh, “Low-Enthalpy Geothermal Resources for Power Generation”, p.112, 2008 CRC Press.

ENGINE, Enhanced Geothermal Network of Europe, Workpackage 5- Deliverable D35.

Geothermie Unterhaching, “Geothermy- a forward looking investment, 2008

Long A., “Improving the econimics of geothermal development through an oil and gas industry approach”,Schlumberger Business Consulting, 2008.

Lund John W., “Small geothermal power project examples”, GHC Bulletin, p. 11, June 1999.

Magyar J., “Perspektívne geotermálne územia v neogéne a podloží Východoslovenskej panvy”, 2001-2008.

Massachusetts Institute of Technology, “The Future of Geothermal Energy”, International Geothermal Association 2006.

McKenna R. J., “CO2 Injection and Sequestration”, Oil & Gas Journal, Week of Sept. 5, 2005, PennWell.

Ministry of Economics of Slovak republic, “Stratégia energetickej bezpečnosti Slovenskej republiky s výhľadom do roku 2030”, November 2007.

Schlumberger D., “Cementing Technology”, Nova Communications Ltd, London 1984.

University of Denver, “Energy Forecasts” http://www.ifs.du.edu/assets/help/WebHelp/ifshelp.htm#energy_forecasts.htm, 2009.